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Military Operations Research

Summer 1994

V1, N1

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MILITARY OPERATIONS RESEARCH SOCIETY

Military Operations Research

A publication of the Military Operations Research Society

The Military Operations Research Society is a professional society incorporated under the laws of Virginia. The Society conducts a classified symposium and several other meetings annually. It publishes proceedings, monographs, a quarterly bulletin, *PHALANX*, and a quarterly journal, *Military Operations Research*, for professional exchange and peer criticism among students, theoreticians, practitioners and users of military operations research. The Society does not make or advocate official policy nor does it attempt to influence the formation of policy. Matters discussed or statements made in the course of MORS symposia or printed in its publications represent the opinions of the authors and not the Society.

Note from the Publisher:
This is the first issue of *Military Operations Research*, the Journal of the Military Operations Research Society. This and other issues published in 1994 will be sent without charge to the entire MORS mailing list. Subsequent issues of the Journal will be sent to MORS members as part of their membership privileges and to government employees covered by our Sponsors. If you are not a MORS member or are not included on the list provided to us by our Sponsors, there will be a subscription charge for additional issues.

A lot of work has gone into planning and publishing this first issue of the Journal. We hope that you find this publication to be of value. As always, the Board of Directors and Staff ask for your comments on this and any of our other publications or programs.

— Natalie S. Addison, Publisher

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Table of Contents

Volume 1, Number 1

Summer 1994

Objective: Become the Journal of Choice

Gregory S. Parnell, Col, USAF
President
Military Operations Research Society

Our first issue of the Military Operations Research Journal is a direct result of the vision, leadership and dedication of several MORS leaders and our MORS Sponsors. For many years, the MORS members and the MORS Board of Directors have discussed the concept of a journal dedicated to military operations research.

In April 91 to June 92, Mr. E.B. Vandiver III, COL James L. Kays, and Professor Peter Purdue successfully proposed the Journal by convincing the Board of Directors, and obtaining support from the Sponsors. Van led the Journal effort as Education Committee Chair, VP for Professional Affairs, and President. Jim was an early supporter and major organizer as he succeeded Van as Education Chair and VP for Professional Affairs. Peter was selected as our Editor and has been responsible for selecting the associate editors, reviewing the papers, and coordinating the administrative details.

Many others have made significant contributions. Without our Sponsors' enthusiastic support (and funding) the Journal would not have been possible. Brian McEnany, our current VP for Professional Affairs, has actively pressed for publication of the initial issue, and has provided guidance for the development of the business plan. Gerry McNichols developed the preliminary business plan. Dick Wiles, our Executive Director, and the MORS staff (as they do on all MORS activities) have made important contributions in planning and publishing the Journal.

Without these efforts, the first issue of our Military Operations Research Journal would not have been possible.

We hope to publish the best military OR analyses and document the military OR art of the leaders of our profession. Simply put, our objective is to become the journal of choice for all military OR analysts!

Solving Real Problems

Dean Hartley
MAS Chairman

For several years we in the Military Applications Section (MAS) of the Operations Research Society of America (ORSA) have been concerned about the lack of articles useful to practitioners in the Operations Research (OR) journals. OR is not mathematics, economics, computer science, or statistics. OR may use techniques from these or other technical disciplines — or it may not. What OR is, is the application of disciplined thought in the effort to solve operational problems. Together with the Military Operations Research Society (MORS), we decided to create this journal to publish articles of interest to the military OR practitioner.

We intend to publish articles about real problems and real attempts to solve the problems. Some of the attempts will be successful; some will involve significant compromises; and some will reflect failures. Some of the efforts described will involve sophisticated mathematics and some will focus on the politics of human nature. In each case the thrust will be in identifying for you the situation, thought processes of the OR practitioners, techniques attempted, and the results. We want our articles to be readable to the majority of practitioners and students of OR. Where detailed and abstruse mathematics are absolutely required (rare), the articles should include an explanation in plain English of the meaning (e.g., this equation shows that such-and-such is true or that it is legitimate to transform the problem in the desired way).

When you read an article, you should be able to compare the problem with those you may face. If you find an approach that is novel and appears useful, you can contact the authors (or research the techniques yourself) for details. If you have faced a similar problem and found (or suspect there is) a better approach, write a note to us. We may publish the note. Or we may ask you to expand the note into an article.

Philosophically, we regard the application of OR to be an art. Even the most experienced can learn from others. We are assuming the authors were doing their best considering time available, talents, resources, and restrictions. Suggesting an alternative approach does not denigrate their efforts. That alternative may not have been applicable to that particular instance, but could be useful in others. Or the authors may not have been aware of the applicability and will learn from your suggestion.

This view of OR also leads to an appreciation of what mindsets are useful (cf., *Zen and the Art of Motorcycle Maintenance).* We will publish some philosophical and historical pieces as they are available to illustrate the possibilities.

Communication is the basic reason for the existence of a journal. Its publication supplies the link from the authors to the readers; however, the link in the other direction requires work on your part. If you have something to say, write me or send an e-mail message. I am the MAS Associate Editor and your ear on the staff. Tell me what you want to see in your journal.

This is *Your* Journal

Peter Purdue
Editor, MOR

This is the first issue of a new journal dedicated to supporting the military operations research community. The journal's aim is to further the development and promotion of the science and practice of military operations research. We will provide the community with a peer-reviewed outlet for information on methodological developments, new and creative applications of existing methodology, and the exchange of ideas on the practical and the speculative aspects of our field. This is your journal!! You are hereby invited to contribute to its health and wellbeing.

The journal will publish original research results, review papers, case studies and notes on all aspects of military operations research. I encourage prospective authors to make their papers complete and interesting, and not to be overly concerned with the length of the paper. Unlike some other journals MOR will not render papers unreadable by requiring their authors to abbreviate them to the point of no return. To facilitate debate on controversial or provocative issues, I will occasionally invite "commentary" pieces from well-known contributors to the field, and allow an exchange of ideas to continue into future volumes. In this way I hope to stimulate some very interesting, as well as technical, discussions in the pages of the journal.

Recent major changes in the world political and military scene have generated many new challenges for the military decision maker. We no longer have the luxury of concentrating on the central front scenario; the threats we face have become much more diffuse, our forces are called upon to play new, non-traditional roles, new technologies present great opportunities as well as challenges. But these uncertainties and frustrations have generated a climate in which the military operations research community has its greatest opportunity to shine since its creation in World War II. The community will have to both adapt some old and reliable concepts, and learn to exploit new ones, like distributed simulation. This should be a very productive time for operations research practitioners, developers, and academicians, as well as for policy makers. It is my hope and desire that the journal will facilitate the fruitful exchange of ideas among all these parties.

As the editor of this new journal, I want to be responsive to the needs and expectations of my readers. So, I encourage you to write to me with any ideas you might have about the journal, and how it may best serve your needs. And, do not hesitate to submit papers for review! The journal will only be as good as the papers it attracts. Join me in this exciting new venture.

Managing Ship Performance of Naval Gunfire Support Using Statistical Process Control

Michael Bailey
Associate Professor
Department of Operations Research
Naval Postgraduate School
Monterey, California 93943

John Bowden
Operations Branch Manager
Crane Division, Naval Surface Warfare Center
Crane, Indiana

Alexander J. Callahan
Senior Engineer
COMARCO
Bloomfield, Indiana

INTRODUCTION

Naval Gunfire Support (NGFS) is a critical capability of the U. S. Navy, and is used to protect amphibious forces. Often, the execution of NGFS is time-critical. The accuracy of the shooting (called fall-of-shot) and the time it takes the gun crew to shoot the gun (called the gun cycle time), are two critical attributes of a mission. If the rounds land on or near the target, and if the gun crew can fire the gun quickly, the NGFS mission is most likely to be successful.

Both of these performance characteristics vary from ship to ship, crew to crew, and mission to mission. There is both bias and variability in the characteristics, and one or both can suffer when some component of the gun system deteriorates. There is immediate feedback within the system in that the crew is continuously apprized of its fall-of-shot accuracy, and any crew member can observe the gun cycle time.

In this work, we develop a novel application of statistical process control (SPC) to fall-of-shot, and to gun cycle times. We will show how control charting can be used during the execution of an NGFS mission, as well as during NGFS training to increase the efficiency of the gun crew and to save costly ammunition and range time.

The purpose of this work is

- to describe how SPC techniques can be effectively used to manage NGFS processes;
- to discuss the practical hurdles in applying SPC to data coming from NGFS qualification exercises;
- to discuss how the use of the results of SPC on NGFS platforms could benefit the management of these platforms and the assets they expend in maintaining readiness.

THE PROCESS

The process of executing an NGFS mission has as its kernel the process of firing a single round accurately. Starting in the gun magazine, where the rounds are kept, a round is retrieved and placed in an automatic loader. The loader system delivers the round to the gun chamber, and the system starts its electronic firing sequence. The sequence is analogous to a series of links in a chain which ultimately ends in the conversion of electrical power into thermal power in the firing pin of the gun. The chain continues as thermal power until the round propellent is exploded. Hereafter, the power is mechanical — the projectile is catapulting toward the target.

As the projectile nears the target, its detonation sequence takes place. This sequence is started by the fuze in the nose of the projectile. The fuze can be mechanically timed, point detonating, or work based on the proximity of the earth. Fusing is determined by the round type and the nature of the target. Once the detonation is witnessed by spotters near the target, an aimpoint correction vector is calculated. This vector is relayed to the gun crew through the command, control, and communications network.

The ship has been underway during the flight of the round, the construction of the spotting vector, and the communications. The gun crew uses a fire control computer and a radar or other navigational system to stabilize the old aimpoint, then corrects the aim of the gun based on the new spotting vector. Often the gun gets a second aimpoint change because of the nature of the target. At this point, the process starts over again.

Statistical process control is a set of techniques used in managing a noisy system we wish to keep stationary in mean and variability. These techniques have been used widely in managing machinery in factories. The goal of many SPC techniques is to provide an automatic method for detecting drastic deterioration of the performance of the equipment, where performance is measured via a set of key performance characteristics. Control charts are simple devices used to establish bounds on measured characteristics, so that when the bounds are exceeded, production should be suspended and the machine in question should be adjusted or repaired.

In what follows, we show how SPC techniques can be used to manage the gun crew's execution of the mission. In particular, we will use control charts to examine the performance of gun systems, where the attributes measured will be cycle time and miss distance.

METHODOLOGY

In this section, we describe the data we will use to control our process as well as the sequence of steps we employed to characterize the behavior of the NGFS target processing system.

The Data

The data we used came from ship exercises performed at Atlantic Fleet Weapons Training Facility (AFWTF), Isle de Vieques, Puerto Rico. We collected data from three (3) different ships, one of which we saw for two qualification exercises separated by twelve (12) months. The other ships were monitored for only one qualification exercise. Hence, we have four observation sets. We recorded the data at the AFWTF observation post, where the exercises are managed.

The exercises are made up of a collection of engagements designed to be challenging, as well as representative of the different NGFS missions that a ship might be asked to perform in battle. The exercises are performed by the ships in a controlled environment where their execution can be observed in detail, and are scored based on the overall performance of the ship. The ships' crews carry these scores as credentials, so the crews are very motivated to perform well.

The exercises involve area and point targets. Each target undergoes a spotting evolution followed by a fire-for-effect evolution. In the spotting evolution the gun system is expected to locate the target and fire a round at it. The round's impact is witnessed by spotters and the gun's aimpoint is adjusted. After the spotters are satisfied that the gun can reliably hit the target, the fire-for-effect evolution begins. During the fire-for-effect, the gun fires a salvo of many rounds with no further guidance from the spotters. Spotting for area targets is significantly different and less demanding than for point targets. Hence, the data associated with each round fired may come from one of four situations — spotting point targets, spotting area targets, firing for effect on point targets, and firing for effect on area targets.

SHIP	CHARACTERISTIC	TOTAL ROUNDS	OK OBS	AFTER FILTER
1	cycle time	72	34	32
1	miss distance	72	26	24
2 (1st)	cycle time	82	25	24
2 (1st)	miss distance	82	24	24
2 (2nd)	cycle time	48	28	28
2 (2nd)	miss distance	48	14	14
3	cycle time	115	65	60
3	miss distance	115	52	52

Table 1: Samples for the different characteristics for the different ships. OK OBSs were rounds which we considered to come from the same distribution as the characteristic we sought. The filter mentioned was for outliers

The upshot of the preceding discussion is that the system we described above is only fully realized during spotting for point targets. Point target spotting rounds are the most complicated to deliver and involve all of the components of the NGFS process. Only a small portion of the data collected were spotting rounds for point targets. The data we analyzed for miss distances included only these rounds, while we were able to accept cycle times from point target spotting rounds as well as some of the area target spotting rounds. As we will see, this makes each one-exercise data set too small to use in off-the-shelf control charts.

The U. S. Navy developed and maintains a set of threat lists for different warfare areas, including NGFS. The NGFS warplan establishes requirements that ships performing NGFS be able to destroy or disable a specified set of targets in a specified time interval. These war plans are used to develop exercises for NGFS qualification, and can be used to develop thresholds for miss distance and cycle times. As the usual manufacturing application has a specification for workstation performance, NGFS platforms have threshold cycle times and miss distances which are derived from the U. S. Navy war plan for NGFS. Evolving capabilities of NGFS platforms are taken into account when the war plan is formulated, thus the goals set out in the war plan are consistent with the ships' process's capabilities.

We recorded two characteristics — cycle times and miss distances. We wish to know:

- Is the time between rounds in control?
- If in control, is the time between rounds low enough or should the war plan requirements be altered to reflect realities seen in the charts?
- Is the miss distance for each gun in control?
- If in control, is the miss distance for each gun low enough, or should the war plan requirements be altered to reflect realities seen in the charts?

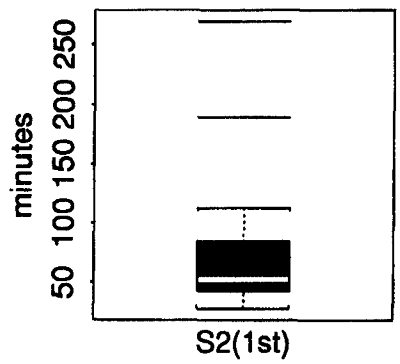


Figure 1: A boxplot for the first exercise cycle times of ship 2. Two outliers were identified for removal.

A Priori Identification of Outliers

Because we were the data collectors during the exercises, we were privileged to listen to ship-to-shore communications. We took notes during the exercises with an eye toward identifying data points which were outstandingly bad, and where there existed known attributable causes for this badness. Due to the nature of the operation, some parts of the process, usually hardware failures, would cause large delays in the delivery of rounds or cause rounds with large miss distances. These conditions are regularly regarded as failures by all concerned, and are treated by repairing the system.

We wished to exclude these data from consideration because we wished to know if the system was in control when the crew thought the system was operational. Many such data were not recorded, but some points found their way into our data. For each data set, we constructed a simple boxplot [4] and possible outliers were identified, see figure 1. The historical account was then referenced to determine if an attributable cause existed to remove the data point.

Each data set was filtered for outliers with attributable causes. The result was that several points were removed from the cycle time data, while only two points were removed from the miss distance data. This was because causes for most large miss distances often involve gun system alignment, and only examination of the gun system itself could confirm misalignment. Furthermore, any misalignment would persist throughout the exercise, so that the resulting large miss distances were not outliers, but consistent. Our only attributable causes were for shots fired at down-slope targets. These target geometries amplify usually small miss distances for the same reason that a round raindrop looks oblong on a slanted windshield.

Preliminary Control Charts

As mentioned above, we employed the short production run SPC techniques as provided in the statistical package MINITAB [8]. We employed the short-run moving average (MA) chart and the moving range (MR) charts.

A prototypical control charting technique starts with the data $X_1, X_2, \dots, X_n$. We group the data into groups $G_1, G_2, \dots, G_g$, each group being of size m. We then take some measurement for each group Gi, eg. the range in disjoint groups $G_1, G_2, \dots, G_g$

$$R_i = \max_{X \varepsilon G_i} X - \min_{X \varepsilon G_i} X.$$

We establish upper (lower) control limit UCL(LCL)

$$UCL = \bar{R} + 3\hat{\sigma}_R;$$

$$LCL = \bar{R} + 3\hat{\sigma}_R.$$

We diagnose the system using a plot of the series Ri along with the control limits. The system is definitely out of control if the control limits are exceeded. Other diagnostics can also raise alarms, eg. a long series of points which are all increasing or decreasing. The control chart we used here as an example is called an R chart, and tells whether the *variability* in the data is consistent throughout.

Small sample control charts typically use small overlapping groups. MA computes the moving averages of the groups using a specified window width w, and uses the moving range as a surrogate for the population standard deviation to produce control limits. Let Gi = {X{(i-1)w + 1}, X{(i-1)w + 2},..., X{(i)w}}, then

$$MA_i = \frac{\Sigma_{X \varepsilon G_i} X;}{g}$$

$$MR_i = \max_{X \varepsilon G_i} X - \min_{X \varepsilon G_i} X.$$

Our small sample MA chart has control limits given by: quality control. This chart is:

$$UCL = \bar{M}A + A_5\bar{M}R;$$

$$LCL = \bar{M}A + A_5\bar{M}R.$$

A_5 is gotten from tables in sources like [1], or any text on quality control. This chart is reputed to have increased sensitivity as compared with other short-run charts, and serves the same purpose — to identify when the measure of central tendency goes out of control [3].

MR charts are used to track the variation of the data. When the process is seen to be out-of-control using MR, the process is displaying an unusually high variability. This can happen even when MA is in control. The chart is formed using control limits:

$$UCL = \bar{M}R + D_5MR_{Md};$$

$$LCL = \bar{M}R + D_6MR_{Md}.$$

where MR_{Md} is the median value of MR_i, $i = 1, 2, \ldots, g$, and D_5 and D_6 are found in tables. As seen in figure 2, our cycle times for ship 3 remained in control for MA but went out of control for MR. The assignable cause for the behavior we see here is that the ship had intermittent visual contact with its navigation reference point. Thus it was forced to hold its fire for short but significant periods of time during some missions.

As a result of the analysis of the control charts for the different ships, we were able to reach the conclusions shown in table 2. From figure 2 we see that the cycle times for ship 3 displayed large variation {\it in its variability}. The MR makes two sojourns outside the control limits. An I chart was also constructed for this case, and it showed one sojourn outside the control limits, as well as seven consecutive decreasing points. These are both signals that assignable causes should be sought.

In the recommendations we form below, ship 3 should have left the firing line early in the qualification process to examine the causes for these chart behaviors. According to current management practices, the ship continued to shoot its qualification missions, used a large number of expensive rounds of ammunition, and received a low score for its qualification for NGFS. Clearly, no one benefits from such an experience.

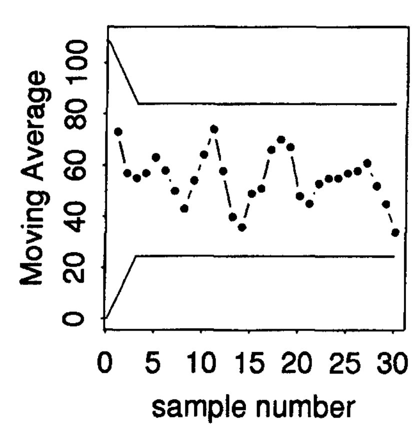
Table 2: Preliminary control charting results.

SHIP	CHARACTERISTIC	MA IN CONTROL	MR IN CONTROL
1	cycle time	Y	Y
1	miss distance	Y	Y
2(1st)	cycle time	Y	Y
2(1st)	miss distance	Y	N
2(2nd)	cycle time	Y	N
2(2nd)	miss distance	N	N
3	cycle time	Y	N
3	miss distance	N	N

Consolidating Data: Historical and Intership Consolidation

As noted, the sample sizes available from a single exercise were too small for proper application of standard control charting techniques. Furthermore, it is clearly desirable to give control limits to ships before they arrive at the AFWTF range to expend some expensive ammunition and range time.

We were inclined to combine the data into a single data set to use for all ships. However, we realized that the data sets came from different



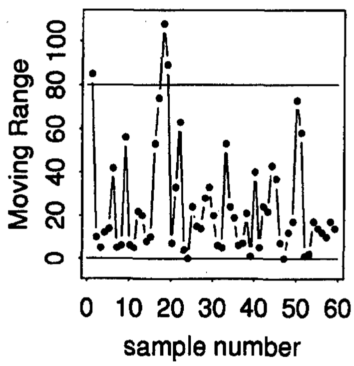


Figure 2: MA and MR for ship 3's cycle time. Note that MA shows the central tendency in control, while MR shows the dispersion to be out of statistical control.

ships and should be treated as data from different workstations in a manufacturing process. Even when we observe the same ship more than once, the interval between visits to the AFWTF range is often more than one year. Hence, personnel on the gun crew can be expected to partially change, the spotting crew will certainly be different, and the command of the ship may even change.

At issue — *Can we combine many ships, or many observations from the same ship, into a single sample to establish control limits?* This proposition can be repackaged as the hypothesis that the ships' data comes from the same distribution.

We constructed boxplots, Q-Q plots, [4] and Kolmogorov-Smirnov (KS) bounds [6] to guide us in deciding if we could combine different groupings and provide more powerful control techniques. Table 3 shows some of the results of our testing.

combination	combine
All cycle times	Y
All miss distances	N
Ship 2 miss distance	Y

Table 3: Results of graphical and nonparametric tests for amalgomating data from different ships and different exercises from the same ship. Conclusion: combine all cycle times into a single data set, combine data from the same ship for miss distance for two observations.

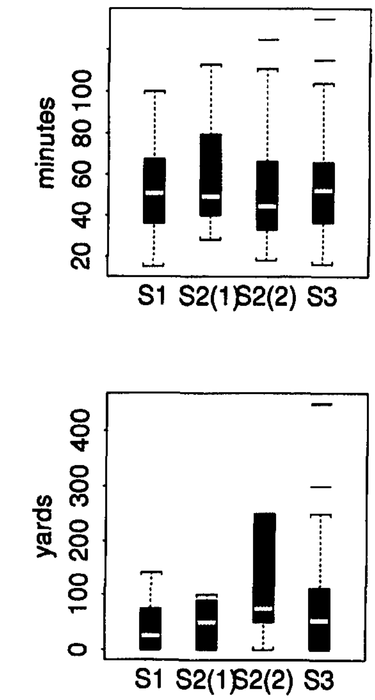


Figure 3: Boxplots for the miss distance and cycle times for the four data sets.

Figure 3 shows the boxplots of the data from the four observation sets. Figure 4 shows the Q-Q plot for the analysis comparing Ship 1 and Ship 3 miss distances. The decisions in the table seem to be consistent with our intuition. The results strongly

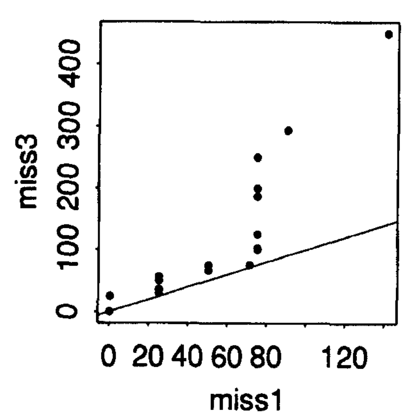


Figure 4: Q-Q plot for miss distances for Ship 1 and Ship 3. Clearly, these data come from different distributions.

suggest that cycle times are similar for all vessels considered. Cycle times are dependent mostly on crew performance — all of the crews are trained at a central facility in Norfolk, Virginia. However, miss distance data for different guns should not be combined. Gun mounts, especially aging systems, may have quirks which make their miss distance behavior unique. Furthermore, these conditions are known to change over relatively short periods of time.

We combined the data as suggested in table 3. We then proceeded with standard X-bar and R charts for the collected cycle times, as well as for ship 2's miss distance data. The result of the cycle time data R chart is seen in figure 5. This R chart showed the systems all in control — a conclusion directly opposed to the one drawn earlier using the short run techniques! Conclusion: *Even though the Q-Q and KS results suggested that we combine the data, this combination*

- *increased variability of the whole sample by introducing between-ship variability;*
- *widened the control limits;*
- *weakened the test for control.*

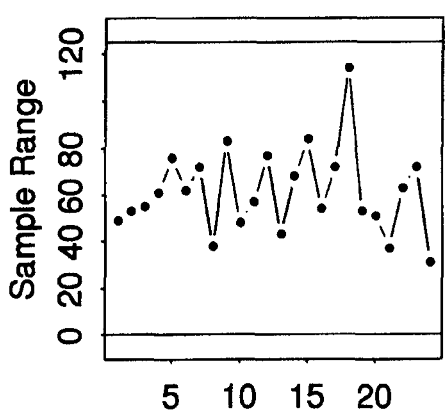


Figure 5: R chart for all of the ships' cycle times.

IMPLEMENTATION

The control charts that have been constructed are useful for the individual ship to use as a gauge of real time performance, and for the team at the AFWTF exercise observation post. The initial use of the control chart for cycle time gives the ship a benchmark for performance that until now has not existed. The control chart can be used to measure performance in a training mode without shooting the gun. Cycle times can be recorded while using the computer simulation of the observation post while away from the range in order to ensure the combat team is operating at an acceptable rate. Such a man-in-the-loop simulation exists [7], and could be used by crews while in transit to the range. Using this simulation, large sets of low-cost data can be collected on the crew performance.

As the ship then moves to the range, the charts again can provide the feedback that the systems are operating within specification. When deterioration is detected, efforts can then be made immediately to determine and correct the cause before a complete set of qualification exercises are completed with less than the desired result.

With regard to the miss distance evaluation, further study needs to be done to determine if this measure can be put in control for each ship. It is suspected that gun system alignment is the likely reason for large miss distances. Evaluation of system alignment and work done on the systems for the three ships involved must be evaluated in order to address this issue, as well as evaluating data from more ships. If gun system alignment is the reason for poor performance, the control chart provided an early warning of a system requiring alignment. This reason is compelling from evaluation of the collected data since the large miss distances seems to be associated with only one of the two mounts on ship 3, indicating that the gun mount is out of alignment. Summarizing, we believe that the following action items are indicated:

- A fleetwide cycle time specification can be established, and each crew arriving at the range should be able to meet the specification while maintaining statistical control. This can be done in a simulated environment before any live ammunition is expended.
- If the crew cannot meet the cycle time specification while maintaining control, they should not be allowed to shoot for qualification until causes are identified and rectified.
- Each ship should maintain its own miss distance control limit, and ship's systems should be evaluated with respect to this control limit during exercises.

- Decision-makers responsible for preparing war plans should be cognizant of ship capabilities and should not plan on gun systems to perform at levels exceeding these limits.
- The Range Control Officer (RCO) should maintain the data on each ships' capabilities and should publish these results Department-wide for each exercise and for each platform. These data would be extremely valuable to decision makers working on any component of naval gun weapon systems.
- The RCO should be provided with technical expertise and software to support their real-time collection and dissemination of control chart data, and should be given authority to suspend exercises or dismiss platforms which are discovered to be out-of-control in mid-exercise. A ship would then start a search for attributable causes for their out-of-control performance. Exercises would resume once the causes were identified and rectified.
- Commanders and decision-makers should be educated on the shortcomings and benefits of employing control charting in NGFS processes.
- Ship's commanders should be prepared to take their platforms off of the gun line if they discover that they are out of control during live missions.
- NGFS readiness of the fleet must be measured in terms of the number of ships able to maintain statistical control in accuracy and gun cycle time.

We believe that the financial investment made in ammunition, in NGFS protected assets, and at AFWTF justify the above. We further believe that other protective missions such as electronic countermeasures, antiradiation missiles, convoy antisubmarine screening missions, preemptive special operations, and antiship missile defenses should be evaluated in ways similar to the NGFS mission.

EPILOGUE

The OPNAV combat systems quality management board (QMB) was briefed on our methodology in May, 1993. COMNAVSURFLANT and AFWTF agreed that our novel application of SPC methodology was promising. These methods are being considered for implementation at AFWTF during qualification exercises in the very near future. It is our expectation that SPC will soon be implemented in combat operational procedures in the future. As per the above recommendations, the QMB also agreed that studies of SPC should be pursued in other defensive warfare applications.

[1] American National Standard: Control Charting Methodologies 1990. Milwaukee: American Society for Quality Control.

[2] Bothe, D. R. 1988. SPC for Short Production Runs. Prepared for the U. S. Army Munitions and Chemical Command, Product Assurance Directorate, Process Control Engineering Division, Rock Island, Illinois.

[3] Buffa, E. S. and R. K. Sarin. 1987. *Modern Production/Operations Management.* New York: John Wiley.

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Sortie Optimization and Munitions Planning

Gerald G. Brown
Operations Research
Naval Postgraduate School
Monterey, CA 93943

Dennis M. Coulter
Headquarters, USAF
Pentagon
Washington, DC 20330

Alan R. Washburn
Operations Research
Naval Postgraduate School
Monterey, CA 93943

ABSTRACT

Since 1965, the United States Air Force has relied on mathematical programming for the planning of conventional air-to-ground munitions. The centerpiece of this planning effort is HEAVY ATTACK, a theater-level model employing large-scale nonlinear programming to load weapons onto aircraft and assign sorties to targets. The single-period objective is to maximize the expected destroyed target value over the forecast weather states by assigning sorties which use the best delivery tactics in each weather state with available aircraft and weapons stocks. Over multiple periods, HEAVY ATTACK accounts for differences between targets in regeneration rate, value, and ease of damage assessment, and evaluates aircraft attrition and remaining weapons stocks, mounting the best sorties possible with the remaining resources. In 1988 approximately $2 billion worth of weapons were purchased with guidance from HEAVY ATTACK; additional expenditures of $5.2 billion are being planned for 1994—99.

In 1990—91, media coverage of Desert Storm made the focus of HEAVY ATTACK apparent to millions of viewers.

> As many arrows, loosed several ways, _ so may a thousand actions, once afoot, end in one purpose, and be all well borne without defeat.
>
> *Shakespeare (Henry V)*

INTRODUCTION

The United States Air Force (USAF) bases its air-to-ground munitions planning on the projected need for weapons in fighting a protracted war. Sufficient stocks of such weapons must be in place in, or transportable to, a theater of operations for timely use in combat. In order to determine the required stores of such weapons, some evaluation of their use in hypothesized theater-level conflict is required.

Over the past 25 years, the USAF has pioneered in the modeling and optimization of the end effects of the procurement, stockpiling, and combat use of conventional air-to-ground munitions; the goal is to provide guidance credible to military planners, to the Legislative and Executive branches of the U.S. Government, and, ultimately, to U.S. taxpayers. USAF is unique amongst the military services in the extent to which it relies on mathematical programming to accomplish this. In 1988 approximately $2 billion worth of weapons were purchased, and expenditures of $5.2 billion are already planned for 1994—99 (e.g., Department of Defense [1993]) with guidance from HEAVY ATTACK, the main subject of this paper. HEAVY ATTACK is one of the major applications of mathematical programming in the United States. In this article we review the history of the system, describe its current use, and project near-term enhancements based on current research.

BACKGROUND

The USAF is interested in optimization because aircraft are flexible weapon systems; depending on how an aircraft is loaded with weapons, it can more or less efficiently attack a variety of targets. Given a collection of several types of aircraft (say a_i aircraft sorties of type i; $i = 1,\ldots,A$) to be used in attacking a collection of targets (say t_j targets of type j, $j = 1,\ldots,T$), the problem of assigning aircraft to targets naturally arises. Perhaps the simplest formulation of the problem would be to let E_{ij} be the average number of targets of type j killed by a sortie of type i, x_{ij} the number of sorties of type i assigned to targets of type j, and then solve program **LP1:**

(LP1)

$$\begin{aligned} \max_{x,y}: \; & \sum_{j=1}^{T} v_j y_j \\ \text{s.t.} \; & \sum_{i=1}^{A} E_{ij} x_{ij} = y_j; \; j=1,\ldots,T \\ & \sum_{j=1}^{T} x_{ij} \le a_i; \; i=1,\ldots,A \\ & x_{ij} \le 0, \end{aligned} \tag{1}$$

where y_j (a variable) is the average number of targets of type j killed and v_j (an input) is the subjectively-assessed value of a target of type j. The meaning of the objective function is "average value of targets killed".

Although (**LP1**) is a good starting point for this exposition, USAF has not to our knowledge ever actually used it. The difficulty is that solutions to such formulations tend to be very extreme in nature. Each aircraft type is entirely assigned to a single target type (i is assigned to j if j maximizes v_jE_{ij}); it is even conceivable that all aircraft types might be assigned to the same target type. Although this kind of solution might be reasonable in a target-rich environment where sorties are hopelessly outnumbered by targets, it is neither realistic nor acceptable in general, even merely for planning purposes.

There are two direct methods of embellishing **(LP1)** so that the solutions are not so extreme. The simpler is to add the constraints $y_j \leq t_j$ (note that **(LP1)** does not involve the data t_j at all) to prevent the possibility of killing more targets on average than are known to exist. Call the resulting linear program **(LP2)**. In **(LP2)**, sorties may be assigned to targets other than their favorite type if the favorite type is exhausted. The Theater Attack Model (TAM) discussed by Might [1987] is a linear generalization of **(LP2)** where variables have additional subscripts corresponding to weather, weapons, etc., so descendants of **(LP2)** are well-represented amongst contemporary military planning models. However, even though **(LP2)** accomplishes the goal of cutting off the extreme solutions while introducing minimal complication to **(LP1)**, it was not the method originally chosen by USAF.

The other direct method of fixing **(LP1)** is to make the objective function *nonlinear* to reflect the idea of decreasing returns as y_j is increased. An early USAF model, SABER MIX, was identical to **(LP1)** except that the objective function was

$$\sum_{j=1}^{T} v_i t_j (1-\exp(-y_j/t_j)) \qquad (2)$$

This objective function might be justified by arguing that the "fog of war" will cause the statistics of the number of times a particular target of type j is killed (say, X_j) to obey the Poisson distribution (Blackett [1962]). Since the expected value of X_j is y_j/t_j, it follows from the Poisson assumption that the probability that any target of type j is *not* killed is

$$P(X_j=0)=\exp(-y_j/t_j).$$

Equation (2) then follows directly. The objective function still has the meaning "average value of targets killed", just as in **(LP1)** and **(LP2)**. Of course the new mathematical program (call it **(NLP1)**) is of a more difficult type; the constraints are linear, but the objective function is not.

Since $1 - \exp(-x) \leq x$ for $x \geq 0$, **(NLP1)** will always have a smaller optimized objective function than **(LP2)**. **(LP2)** essentially incorporates the assumption that sorties can be coordinated so that targets that have already been killed will not be further attacked. This kind of coordination is assumed to be impossible in **(NLP1)**, with the attendant possibility of wastage due to overkill. The two programs correspond to extreme assumptions about the kind of command and control that can be exercised in battle.

(NLP1) was a nontrivial optimization problem when it was formulated in the 1960's. An early attempt at a solution involved the assumption that *all* targets were to be attacked by *one* aircraft type. This problem has the same mathematical form as the corresponding Search Theory problem of allocating random search effort to a collection of cells (Charnes and Cooper [1958]), so an efficient solution technique was available by the time the Munitions Planning Branch was formed. However, there were obvious problems with assigning each aircraft type as if none of the others existed, so the desirability of solving the joint optimization problem where all aircraft types are considered simultaneously was quickly recognized.

In the early 1970's, the Directorate of Defense Program Analysis and Evaluation (DDPA&E) funded a mathematical programming-based scheme for assigning aircraft to targets that incorporated the best features of SABER MIX and two other systems that were then in use. The resulting formulation **(NLP2)** is reported in Clasen, Graves, and Lu [1974]. The **(NLP2)** objective function is similar to that of SABER MIX except for the incorporation of an additional parameter c_j:

$$\sum_{j=1}^{T} v_j t_j (1-\exp(-c_j y_j/t_j))/c_j. \quad (3)$$

Note that (3) is the same as (2) if $c_j = 1$, and that (3) is the same as (1) in the limit as c_j approaches 0. The parameter c_j thus bridges the situation where command and control is impossible (the Poisson case $c_j = 1$) and where it is perfect (the linear case where c_j approaches 0). However, a precise meaning for c_j has never been given. Clasen, Graves, and Lu say only that "DDPA&E suggested this function to us. It is similar to the objective function of the SABER MIX methodology." The lack of a physical meaning has proven to be troublesome for subsequent generations of USAF officers (see Embellishments) required to estimate c_j for various classes of targets, and various levels of engagement "fog" in the theater.

(NLP2) also incorporates constraints on y_j that ensure that not more than t_j targets of type j are killed, on average. Thus **(LP2)** and **(NLP1)** are both special cases.

HEAVY ATTACK

The HEAVY ATTACK model currently in use by the USAF Weapons Division is still, at its heart, the Clasen, Graves, and Lu model **(NLP2)**, but now larger and embellished with additional types of linear constraints. HEAVY ATTACK considers a sequence of allocation problems, with each problem corresponding to one time period in a war that is projected to be several time periods long. Targets that survive the attacks of one period are still available in the next, together with reinforcements and also with targets that were killed in previous periods but have since been repaired (reconstituted), possibly with different values. The optimization is done myopically, with the objective in each period being to kill as much target value as possible without regard to the effect on future periods. The myopic feature is analytically convenient, since it permits the analysis of a sequence of small problems rather than one large one, but it is also realistic in the sense that the actual policy for assigning aircraft to targets (which must be distinguished from the value-based method in HEAVY ATTACK) is a joint-service process that does not include the idea of "saving targets for the future". There may be an element of making virtue out of what was once a necessity here, but still that is the justification usually given for myopia.

HEAVY ATTACK depends on a separate program, SELECTOR, for the sortie effectiveness inputs E_{ij}. SELECTOR is needed not because effectiveness coefficients would otherwise be lacking, but rather because there are too many of them. The Joint Munitions Effectiveness Manual (JMEM, e.g. Joint Technical Coordinating Group/ Munitions Effectiveness [1980]) shows how to tabulate

E_{ijtw} = average number of targets of type j killed by a sortie of type i using tactic t in weather type w.

SELECTOR's role is essentially to get rid of the last two subscripts. The method for doing this is important, since it is often the case that the most effective tactics are associated with expensive munitions or high attrition to the delivering aircraft. SELECTOR adopts only the most cost-effective tactic: literally the tactic that maximizes the ratio of sortie cost (including the cost of weapons used and expected attrition) to E_{ijtw}. Let this tactic be $t^*(i, j, w)$, and let $E_{ij\cdot w}$, be the effectiveness when that tactic is used. The coefficients E_{ij} required by HEAVY ATTACK for *each period* are obtained by simply averaging $E_{ij\cdot w}$ over whatever weather distribution is appropriate in the area of the supposed conflict; the natural notation would be $E_{ij\cdot\cdot}$, but we will drop the two dots to be consistent with earlier usage. $t^*(i, j, w)$ may change from period to period as stocks of the requisite weapons become exhausted. The weather distribution may also change from period to period, so the same is true of E_{ij}. Crawford [1989] concludes that usage of HEAVY ATTACK with E_{ij} computed in this manner biases weapons purchases towards cheap but inefficient weapons. He reasons that the real "cost" of attrition considerably exceeds the aircraft flyaway cost used by USAF in determining "bang-per-buck."

The inputs to HEAVY ATTACK are determined once each year for each potential theater of operations. The Weapons Division hosts an annual theater planning session attended by mid-level operational, intelligence, logistics, and planning staff officers. The goal is to produce a realistic current requirement for theater weapons stocks. Attendees must travel great distances to participate in these sessions, and can only be expected to remain briefly in residence before returning to exigent duty. Cadre analysts (e.g., Coulter) are responsible for care and feeding of HEAVY ATTACK, and thus must interpret the proposals of the theater planning group and endeavor to provide compelling scenarios for their evaluation. Once HEAVY ATTACK has determined sortie-to-target allocations for each period of the war, munition requirements can be recovered by recalling the function $t^*(i, j, w)$ determined by SELECTOR and doing the appropriate accounting. The resulting estimates of theater weapons stocks requirements are used to justify the aggregate USAF annual weapons buy request. These budget requests are exposed to exhaustive scrutiny by USAF, and subsequently by other levels of review. Budget revisions by higher authority are reconciled with mission requirements with the help of HEAVY ATTACK.

EMBELLISHMENTS

HEAVY ATTACK as first formulated by Clasen, Graves, and Lu in 1974 was a nonlinear program with at most 10 sortie types and 45 target types; even with their new method, solving problems of that size required quite a while on contemporary computers. Enriching the model in any manner that would have increased run times was out of the question, however nervous its users might have been about such things as the SELECTOR/HEAVY ATTACK system's myopic approach to optimization over time, fractional sortie assignments, and the suboptimization implicit in SELECTOR's preprocessing of the JMEM effectiveness data.

However, computers and computer software have improved substantially since 1974. Lord [1982] reports mainframe solution times measured in seconds, rather than minutes, upon completing the installation of the X-system solver (e.g., INSIGHT [1990], and Brown and Olson [1994]). Bausch and Brown [1988] describe a prototypic implementation of HEAVY ATTACK on an 80386-based IBM-compatible microcomputer, an uncommon feat at the time. In 1991 more powerful 80486 machines were configured for production use in various environments, implemented with mainframe-compatible software (Silicon Valley Software [1991]), and shipped to users as HEAVY ATTACK machines. Wallace [1992] exploits this new capability by designing and implementing a prototypic graphical user interface (GUI) which is especially useful for comparing outputs from multiple scenarios. Bradley, et al. [1992] give an unclassified demonstration of this unified hardware and software decision support system: sortie optimization for 25 aircraft types, 90 weapon types, and 100 target types, problems with hundreds of constraints and thousands of variables for each of 6 time periods, requires about two minutes from SELECTOR input to final output. Washburn [1989] describes a new method tailored to the HEAVY ATTACK problem that solves (**NLP2**) with 13 sortie types and 61 target types in about two seconds on an 80386 machine. Plainly, the computation time considerations that drove the original (**NLP2**) formulation have now been substantially relaxed, to the point where more computationally stressful reformulations can be considered.

However, SELECTOR/HEAVY ATTACK's long and successful lifetime as a planning tool makes it difficult to consider *any* substantial reformulation, even now that computational cost is negligible. Generations of Air Force officers have learned to cope with the idiosyncrasies, assumptions, and data requirements. Inter-organizational relationships have evolved to provide inputs and interpret outputs. *"If it ain't broke don't fix it."*

So the Weapons Division is naturally attracted most by changes that merely affect computational efficiency or ease of use. For example, linear side constraints can now be used to insure flyable mixtures of sorties. Graphical user interfaces are expensive to design and develop, but are invaluable for quick, reliable formulation of input scenarios and interpretation of their output. Further, although HEAVY ATTACK can run on many hardware platforms, and employs the fastest large-scale optimizer in our experience, a 486 PC is now the favored host due to its low cost, convenience, and portability. In early 1993, theater conferences were completed for the first time without requiring the physical attendance of the theater planners.

Less favored, but sometimes essential, are changes that produce the same output quantities from the same input quantities. For example, a variety of changes have been made to the target reconstitution model. These changes do not require new inputs nor change the meaning of the outputs, although the output quantities are of course affected.

Least favored are reformulations that require an essentially different way of looking at things. Recently, constraints on weapon usage by period have been added. The basic idea of SELECTOR/HEAVY ATTACK is to buy whatever weapons are required to fight a cost-effective war, so it would seem illogical to include constraints on the usage of a particular weapon. The trouble is that certain weapons (AGM-65A/B Maverick air-to-ground missiles, for example) are no longer in production but still quite effective. The only realistic way to handle such weapons is to constrain their usage to the size of the current stockpile.

Note that the current system includes no budget constraints, even though it is a principally budgetary tool. SELECTOR utilizes cost inputs in determining the most cost-effective tactic, but weapon usage is not actually constrained by any budget. The HEAVY ATTACK output can therefore be interpreted as the classic military "requirements" for weapons with some implied budget level B. The idea that B should be an input, rather than an output, requires a fundamentally different view of the problem.

We continue to pursue enhancements and reformulations. Boger and Washburn [1985] describe an alternate nonlinear objective function where the parameter c_j has a physical interpretation. They also describe how the organization of computations in SELECTOR could lead to overutilization of weather-specialized weapons and weather robust aircraft. Wirths [1989] develops several prototypic reformulations using the GAMS/ MINOS system (e.g., Murtagh and Saunders [1984], Brooke, et al. [1992]). Amongst other things he derives a differential equation for which (3) is a solution, shows that the impact of using a linear objective function is not as great as had previously been thought, and asserts that the myopic approach to optimization over time is possibly of more concern. Utilizing a linear objective function would of course open up a great many other possibilities for reformulation, including the adoption of the conceptually simpler, but larger TAM (Might [1987]), which includes subscripts for weapons, weather, and, according to Jackson [1988], one-dimensional sortie range and time period too. However, TAM utilizes budget constraints, and our computational experience with TAM, as well as that of Jackson [1988], shows that it is very time consuming to solve in spite of its linear objective function.

CONCLUSION

We chose HEAVY ATTACK for this expository paper for some reasons not yet discussed. HEAVY ATTACK has for some time been a favorite classroom example at the Naval Postgraduate School. HEAVY ATTACK is simple to explain and understand without resorting to excessive mathematics, can be used in hands-on homework and modified for experiments by students, yet exhibits all the features, man-machine interaction, and richness a decision support system should have. The system has been in use for many years, and its remarkable longevity and direct influence on billion-dollar decisions automatically enhance student interest and warrant study of its design and application. Even issues of client and analyst psychology, the influence of politics on decision making, and techniques for preserving run-to-run solution persistence and comparison of optimized results can be highlighted. Being a nonlinear optimization model, it also provides rich collateral mathematical material such as characterization of concavity, numerical analysis, function approximation, aggregation, and proofs of convergence.

When the problem description for HEAVY ATTACK is given as a homework formulation exercise, students immediately construct detailed linear models: we call this approach the "$x_{subscript\text{-}foreverything}$" method. Asked to provide answers to the problem under time pressure, students quickly discover the large size and data appetite of their models, and devise reasonable aggregation strategies sometimes reminiscent of HEAVY ATTACK. Required to interpret their answers to this problem, students face many of the paradoxes inherent in modeling.

HEAVY ATTACK is an important member of a standard set of models we use to test new optimization techniques. The fact that we have always maintained nonlinear optimization capability in all our systems has derived in part from consideration of this application. We admit some professional satisfaction that HEAVY ATTACK has evolved, with many cohort models, from a daunting computational feat to a keystroke quick application, even for a microcomputer.

ACKNOWLEDGMENTS

The Air Force Office of Scientific Research and the Office of Naval Research have supported our basic mathematical research in optimization and encouraged its application. The Naval Postgraduate School promotes research on important problems even when there is no direct benefit for the Navy. Insight, Inc. of Alexandria, Virginia, has provided optimization software for HEAVY ATTACK. We thank the Air Force for the opportunity to publish this account in the unclassified literature.

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Modeling and Simulation for the New Pacific Community: A USPACOM Perspective

David G. Haut and Michael L. McCurdy

Mailing Address:
Commander in Chief
USCINCPAC
Attention: J53 (Mr. Haut)
Box 64015
Camp H.M. Smith, HI
96861-4015

ABSTRACT

As the geopolitical situation has changed, the nature of national security has also changed, and with it the roles and missions of the U.S. military. This paper examines these changes, and their implications for modeling and simulation, from the perspective of the U.S. Pacific Command (USPACOM). It presents some of the implications of recent geopolitical changes for military operations research, systems planning, and related pursuits. The paper presents an overview of USPACOM and its strategy, then discusses recent changes in planning and operations and corresponding changes in military operations research. It then presents an assessment of our modeling, simulation, and operations research capabilities for supporting planning, operations, and training. It argues that models developed during the Cold War for large-scale military operations are mature, but are not well-suited for many types of operations that we are likely to conduct in the foreseeable future. Such operations include peacetime activities and operations in addition to low- to mid-intensity conflicts. The modeling and simulation challenge posed by the current geopolitical situation is to understand the phenomena underlying these operations and to exploit this understanding to develop models that are useful to several functional communities.

INTRODUCTION

This paper examines recent geopolitical changes from the perspective of the U.S. Pacific Command (USPACOM). It presents some of the implications of these changes for military operations research, systems planning, and related pursuits. The paper starts by presenting an overview of USPACOM and its strategy, then discusses recent changes in planning and operations and implied changes in military operations research. It then presents an assessment of our modeling, simulation, and operations research capabilities for USPACOM and the New Pacific Community.

USPACOM OVERVIEW AND STRATEGY

USPACOM is the oldest and largest of the United States' nine unified commands, with an area of responsibility (AOR) covering more than 100 million square miles (more than half the earth's surface). The AOR comprises the Pacific and Indian Oceans and more than forty nations, which include some of the United States' most important allies and trading partners. About 354,000 Army, Navy, Air Force, and Marine Corps personnel are presently assigned to USPACOM, about a third of whom are forward-deployed.

USPACOM's strategic objectives depend on the specific situation. In peacetime, our primary objective is to maintain and improve U.S. engagement and participation with the nations in our AOR. In crisis, our strategy is to deter escalation to warfare. However, if conflict does occur, our strategy is to win it on terms favorable to the U.S. and its allies and friends. We view conflict as a double failure: failure to engage and participate during peacetime and failure to deter during crisis.

With the dissolution of the Soviet Union, we are no longer in a bipolar world, as we have been for the last forty years. Accordingly, we are learning to deal with a polycentric world. In our theater, Japan, Korea, China, and India are emerging centers of power. We are working on integrating political, military, economic, and security policies, something we have not done very well in the past. With the closing of U.S. bases in the Philippines, we must develop presence alternatives. We are moving towards a mobile, flexible force structure that includes forces from all of the Services and can be rapidly tailored into sustainable force packages to meet likely requirements. We anticipate that many of these requirements will require the use of joint forces; furthermore, we anticipate that most of the time we will operate as part of a combined, multi-national force. Finally, because of the size of the USPACOM AOR, prepositioned materiel and strategic and intra-theater transportation will be critical components of our ability to deploy and sustain forces.

CHANGES IN MILITARY PLANNING AND OPERATIONS

Not long ago, if asked to prioritize planning for likely conflicts, most U.S. military operations research analysts would have placed planning for global conflict at the top of the list, followed by planning for major regional contingencies such as the Middle East and Korea, with planning for lesser regional contingencies at the bottom of the list. The end of the Cold War has stood this list of planning priorities on its head. Lesser regional contingencies, which include such operations as noncombatant evacuation, disaster relief, foreign humanitarian assistance, and contingency response, are now near the top of the list.

Figure 1 shows the Continuum of Operations, which relates the likelihood of different kinds of operations to the geopolitical situation (peace or conflict) and the level of conflict. The most likely operations are peacetime operations and lesser regional contingencies. The remaining operations are major regional contingencies and global and nuclear conflicts. The shape of the curve in Figure 1 is different than several years ago, when likelihood would have dropped exponentially as the level of conflict increased.

Many of the peacetime operations and lesser regional contingencies will be planned and executed using the crisis action procedures prescribed by U.S. Joint doctrine [1]. Crisis action procedures comprise six phases: situation development, crisis assessment, course of action (COA) development, COA selection, execution planning, and execution. Implementing these procedures involves organizations ranging from the National Command Authority and the Joint Chiefs of Staff to the Service or functional commands subordinate to a Joint Task Force commander. Because contingencies may develop quickly, the entire crisis action process may be executed over a period of hours to days or weeks, a period much shorter than the seven-phase, two-year process we used for deliberate planning. Crisis action phases may be compressed, eliminated, and occasionally even executed out of order.

The difference between crisis action planning and deliberate planning is as great as the difference between black and white. The detailed operations plans (OPLANs) we developed for global

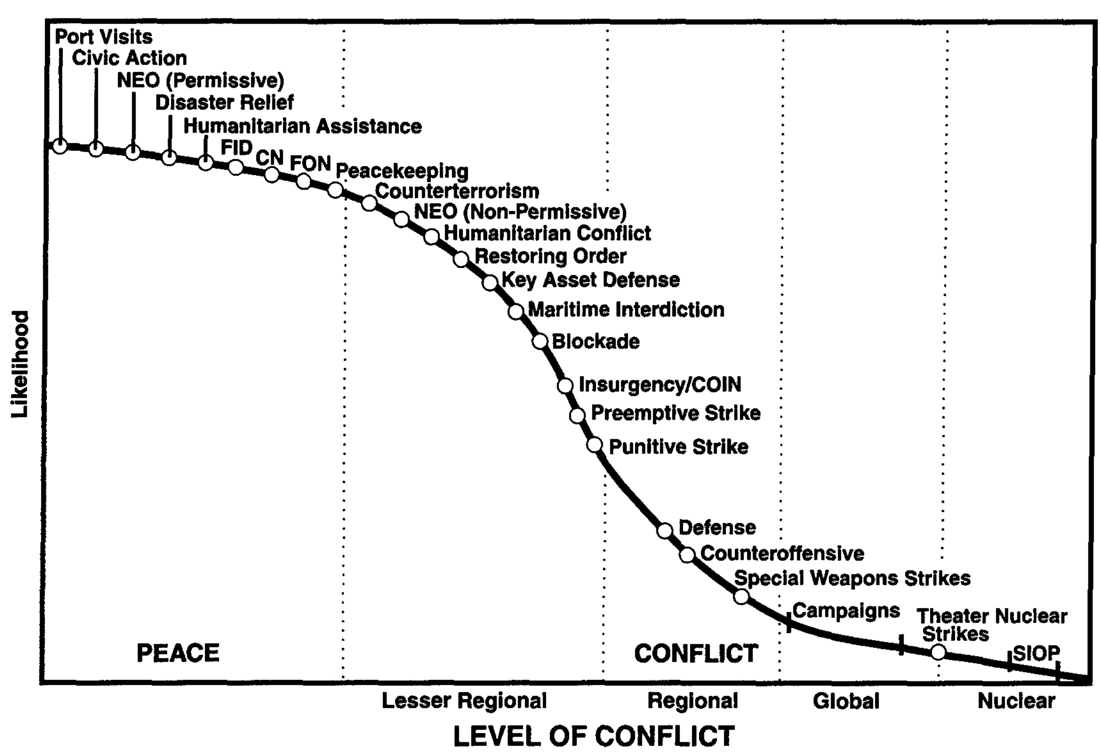

Figure 1. Continuum of Operations

conflict called for multiple, overlapping campaigns, each with its own deliberate plan for deployment and execution. In contrast, for lesser regional contingencies, we have generic concept plans (CONPLANs), one for each class of potential situations. Regional contingencies typically consist of a single campaign that is planned and executed using crisis action procedures. In a global conflict, we would use a three-tier command structure that includes Service component commands such as the Pacific Fleet (PACFLT), Pacific Air Forces (PACAF), and U.S. Army, Pacific (USARPAC) in the operational chain of command. In regional contingencies, we will use a two-tier command structure, which will be described below. In global conflict, the commanders and forces are essentially pre-determined, whereas for regional contingencies we would choose commanders and forces from among those available. Lastly, the deliberate planning process is highly structured and ponderous, as compared with the crisis action procedures, which are designed to respond to rapidly developing situations.

Figure 2 shows the two-tier command structure, which USPACOM now considers its primary command structure. In this structure, Commander in Chief, U.S. Pacific Command (USCINCPAC) exercises direct operational control over a Joint Task Force (JTF) commander, who is selected for a particular operation. This implies that the JTF commander is pulled out from under the operational control of his Service component commander for the duration of the operation. The JTF commander's staff is augmented with members of the USPACOM Deployable Joint Task Force Augmentation Cell (DJTFAC), a response cell that assists the task force commander's staff in operating as a joint headquarters. Army, Navy, Air Force, Marine Corps, and special operations forces are assigned to the JTF based on the specific situation. USCINCPAC's Service component commands act as extensions of the USCINCPAC staff as well as providing logistic and administrative support.

In addition to the DJTFAC, there are several organizations that are either new or have new roles to play in regional contingencies. At USCINCPAC headquarters, these include the Operations Planning Team, Crisis Action Team, special teams (e.g., for deployment or logistics), and the battle staff, which consists of the CINC and the staff's flag and general officers.

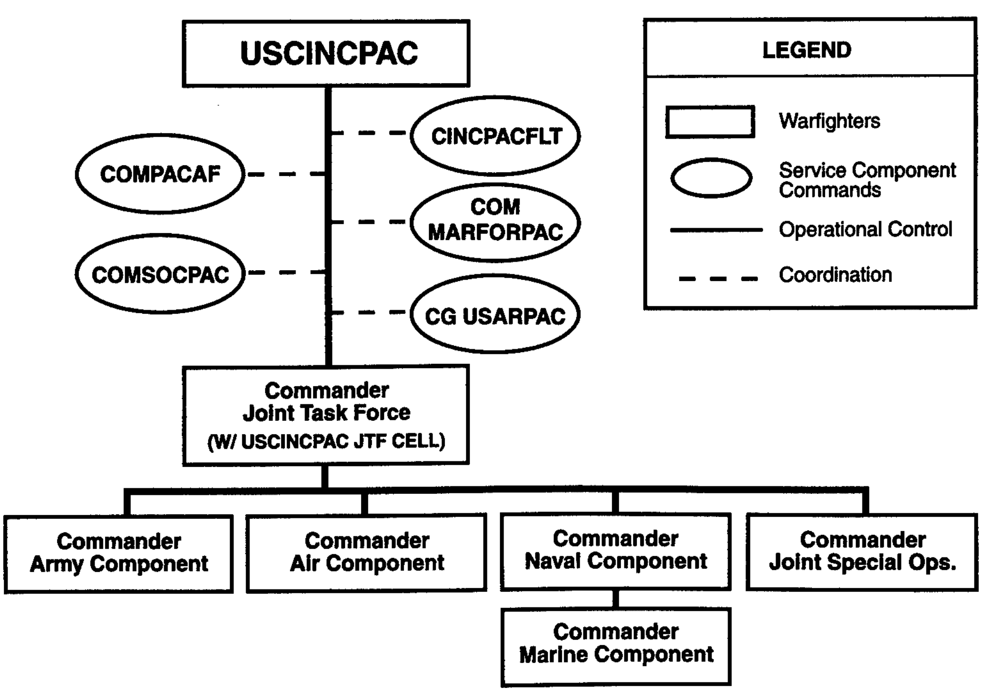

Figure 2. Two-Tier Command and Control Structure

Throughout the theater, these organizations include designated candidate JTF commanders and their staffs and the commands that may be assigned as JTF Service component commands.

A Joint Task Force commander must operate with a wide variety of organizations. He must maintain communication with USCINCPAC headquarters for operational direction and reporting. He must be able to receive information from intelligence sources. He must be able to establish and maintain liaison with the U.S. ambassador and country team and the friendly military in the country where the contingency is occurring. He must be able to communicate with his Service component commands and special operations forces, as well as with the DJTFAC while it is in transit. Finally, he must be interoperable with a simulation driver for training.

CHANGES IN MILITARY OPERATIONS RESEARCH

There are three changes in military operations research that affect us as we address the dynamic world situation: the common interests of diverse functional communities, broader aspects of national security, and emerging technologies for linking and dis tributing models. The last of these is peripheral to the primary subject of this paper and is discussed in Appendix A.

Common Interests of Diverse Functional Communities

Over the past several years, many of the functional communities within the U.S. Department of Defense have come to realize that they have substantial common interests. Figure 3 illustrates these. The functional communities include developers and users of training simulations; wargamers; those involved with field analysis (the observation, reconstruction, and analysis of operations and exercises); analysts supporting deliberate planners; an emerging community providing real-time analysis support for operations; and personnel supporting professional military education, test and evaluation, and system acquisition. An assessment of the state of the art in modeling and simulation to support these communities is presented below for the five communities in the central "rosette" of Figure 3: training simulations, deliberate analysis, real-time analysis, wargaming, and field analysis.

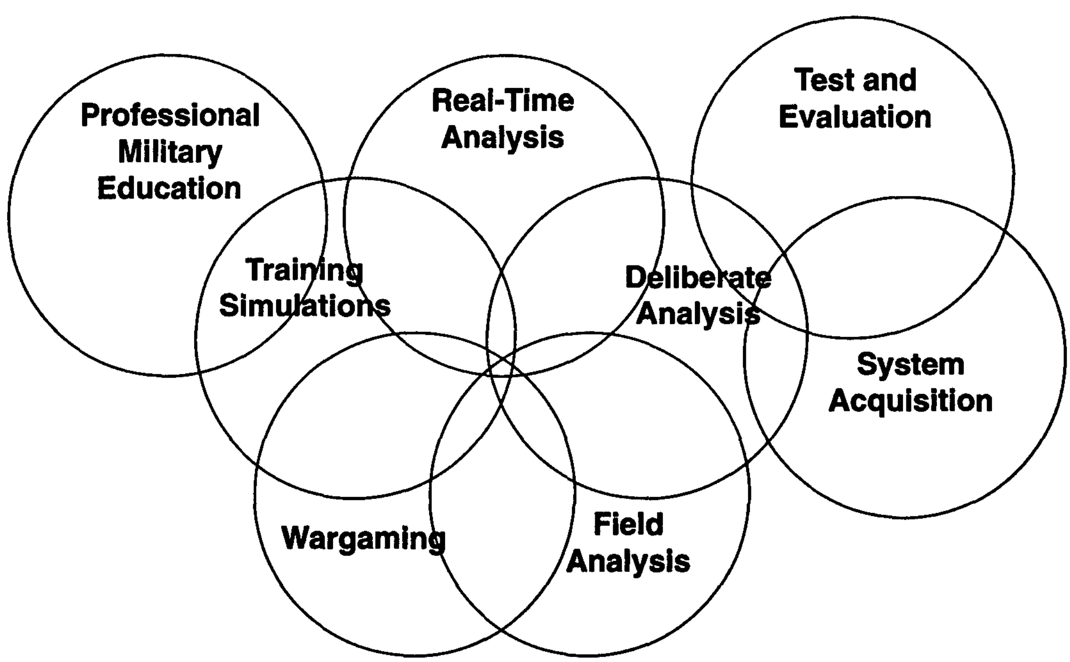

Figure 3. Common Interest of Diverse Functional Communities

Broader Aspects of National Security

Until recently, "national security" was synonymous with warfighting in the minds of many U.S. military operations researchers. However, the changes in the geopolitical climate now make adopting a broader concept of national security desirable. This concept includes the traditional military, non-traditional military, and non-military aspects of national security.

The traditional aspects of national security are the ones U.S. military operations research analysts have been analyzing for the last forty years, and include regional defense, regional counteroffensive, special weapon strikes, campaigns, theater nuclear strikes, and the Single Integrated Operations Plan (SIOP).

The non-traditional military aspects of national security fall into three categories: peacetime activities, peacetime operations, and low- to mid-intensity conflicts. Peacetime activities include security assistance, technology transfer, international conferences, combined exercises, port visits, and civic action programs. As a community, we have done little to analyze the contribution of these activities to national security. Peacetime operations are conducted in response to specific situations, and include permissive non-combatant evacuation, disaster relief, humanitarian assistance, foreign internal defense, counter-drug operations, freedom of navigation, and peacekeeping. We need to be able to quantify the effects of these operations on national security. Low- to mid-intensity conflicts include counter-terrorism, uncertain or hostile noncombatant evacuation, humanitarian conflict, restoring order, key asset defense, maritime interdiction, blockade, insurgency and counterinsurgency, and preemptive and punitive strikes. For many of these conflicts, we do not understand the underlying phenomena or have models to describe them.

The non-military aspects of national security include its diplomatic, political, economic, and cultural/social aspects. We need to understand the issues in these areas as they relate to specific conflicts or situations.

STATUS OF MODELING AND SIMULATION

We will assess the ability of modeling and simulation to support the needs of the U.S unified com-

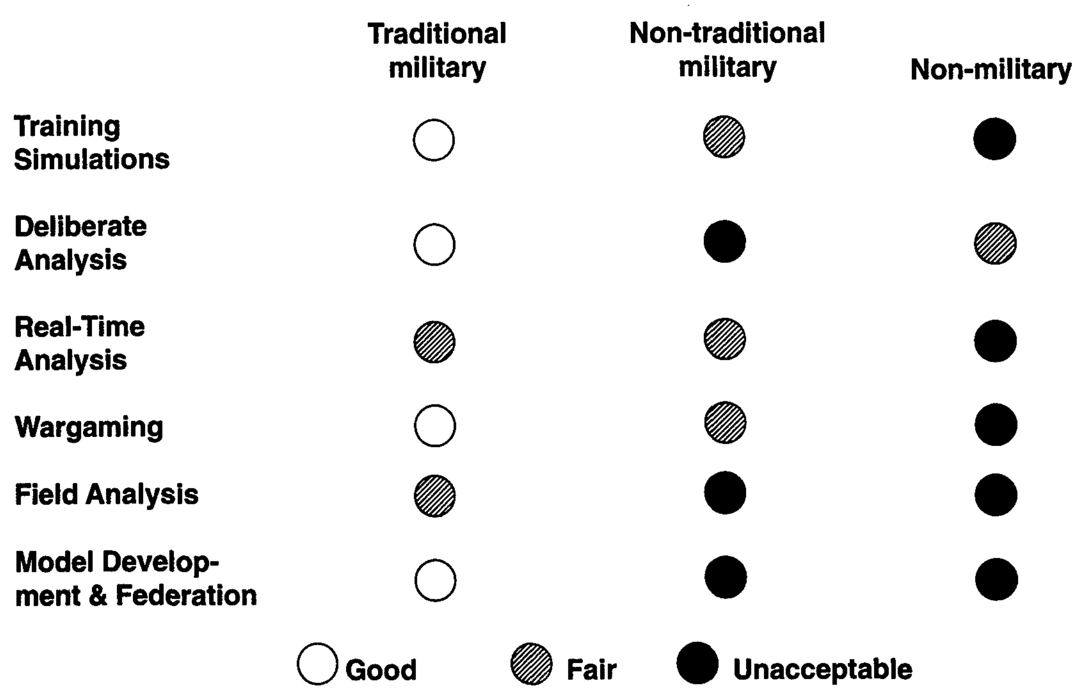

Figure 4. Modeling and Simulation Summary

manders. A summary of this assessment is presented here. Appendix B presents individual assessments for each of the functional areas in the central rosette of Figure 3.

Figure 4 summarizes USCINCPAC's assessment of U.S. modeling and simulation capabilities in "stop light" format. Modeling and simulation of the traditional military aspects of national security is well-developed. Modeling and simulation of non-traditional military activities and operations requires substantial development. For many of these activities and operations, the underlying phenomena need to be understood before modeling should be attempted. A combination of research into these phenomena and model development is needed for these activities and operations. For the non-military aspects of national security, most of the underlying phenomena are not understood well enough to support development of credible models; emphasis should be almost exclusively on researching the underlying phenomena.

Based on these assessments, the U.S. needs to put most of its emphasis in modeling and simulation on developing models for non-traditional military activities and operations while simultaneously pursuing research in the non-military aspects of national security. This approach will allow us to adapt to the changes in operations and planning that have accompanied recent geopolitical changes.

CHALLENGES FOR THE MILITARY OPERATIONS RESEARCH COMMUNITY

What challenges do recent geopolitical changes pose for the military operations research community? There are at least two: dealing with the Continuum of Operations, and developing a Joint mindset.

Dealing with the Continuum of Operations

Figure 1, presented at the beginning of this paper, displayed the Continuum of Operations. With the end of the Cold War, the activities and operations we are most likely to conduct are those in the boxed area, i.e., peacetime activities and operations and low- to mid-intensity conflicts. Because of our preoccupation over several decades with analysis to support major regional contingencies and global and nuclear conflicts, we are ill-prepared to provide analysis at the lower end of the Continuum of Operations. One challenge for the military operations research community is to assist in redirecting military operations research towards the non-military aspects of national security and non-traditional military activities and operations.

Developing a Joint Mindset

Another challenge for military operations researchers is to develop a Joint mindset. GEN Powell signed "Joint Warfare of the US Armed Forces" (Joint Pub 1) [2] in November 1991. It contains numerous quotes, some dating back to the Civil War, indicating the importance of Joint operations. The United States' World War II Service chiefs all recognized the major role played by Joint operations.

Moreover, there is more than one definition of "jointness". One of these, which Mr. Vincent P. Roske of the Joint Staff's Force Structure, Resource, and Assessment Directorate refers to as "Joint_1", indicates cases where there is high Service interest and consequent availability of Service resources. The second definition of jointness, "Joint_2", is characterized by low Service interest and hence greater use of OSD, Joint Staff, and unified command resources. Joint_2 examples include training JTF staffs and improving CINC command centers.

In a recent article [3], Admiral William Owens points out that there are two competing views of jointness in vogue. These are specialization, which holds that the Services should stick to the roles for which they were established, and synergism, which holds that the military capabilities of the Services should be blended in response to a specific situation. In the former view, the capabilities preexist, whereas in the latter they must be combined on an *ad hoc* basis. Admiral Owens states that neither view has gained ascendancy so far, but that the Armed Forces must define the practical meaning of joint operations and then adopt it as second nature. He feels that synergism is the more compelling view, because it draws on common ground that the Services have developed through joint exercises, operations, and war games.

One example of the challenges involved in developing a Joint mindset is field analysis of joint operations and exercises. For many years, the U.S. Navy has had a strong program of field analysis to assist with the development of naval tactics and doctrine. The challenge is to develop a similar program to facilitate doctrine development for joint (and, by extension, combined) operations and exercises.

Along with many other organizations, the military operations research community should accept the challenge to develop a Joint mindset.

SUMMARY

This paper has presented an overview of USPACOM and its strategy for dealing with recent geopolitical changes. It has discussed changes in planning and operations and in military operations research. It has presented an assessment of modeling and simulation capabilities to support the activities and operations we expect to conduct in the foreseeable future. Key points are listed below.

- As geopolitical changes have occurred, the types of activities and operations USCINCPAC expects to conduct most frequently have also changed. Many of these are peacetime activities and operations or low- to mid-intensity conflicts. For some of these operations, we have generic concept plans; however, many will be "no plan" situations.
- The need to respond rapidly to peacetime and regional contingencies has led USCINCPAC to adopt two-tier command and control as its primary command and control structure.
- Military operations research is changing to recognize the common interests of diverse functional communities, broader aspects of national security, and emerging technologies for distributing and linking models.
- New modeling and simulation requirements arise from the common interests of diverse functional communities. These include training simulations for Joint readiness, deliberate analysis, real-time analysis, wargaming, and reconstruction of operations and exercises.

As a result of recent geopolitical changes, the U.S. military operations research community faces a significant challenge in developing models and simulations for the operations we will conduct most frequently. To meet this challenge, we must deal with the Continuum of Operations, especially at its lower end, and develop a Joint mindset that reflects the interests of OSD, the Joint Staff, and the unified commands as well as the Services. If we accept this challenge, we will be a major force in assuring national security for the foreseeable future.

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Appendix A

EMERGING TECHNOLOGIES FOR LINKING AND DISTRIBUTING MODELS

At the same time geopolitical changes have made it necessary to take a broader view of national security and diverse communities within DoD have started to recognize common interests, technologies have emerged that make linking and distributing models easier. One of these is the Defense Simulation Internet (DSI), an Advanced Research Projects Agency (ARPA) initiative. DSI links about 65 sites from Korea to Europe via a high-speed dual-backbone communication system. It provides the capability to rapidly transfer models and data between sites and also provides video teleconferencing.

There are also several technologies emerging for linking models. Three of these, Cronus, Data_Bus, and the Aggregate Level Simulation Protocol (ALSP) are discussed below; other approaches also exist.

Cronus was developed for ARPA and has been used in the Capabilities Assessment, Simulation, and Evaluation System (CASES) at Headquarters, U.S. Pacific Fleet. It was also used in the Dynamic Analysis and Replanning Tool (DART), a model for assessing the feasibility of deployment plans. Cronus automatically handles communications between models hosted on different computers, allowing a "federation" of models to run on a network of computers that have widely varying characteristics. It allows interactions between models, but needs specially-designed software to synchronize model execution. Using Cronus requires some modification to the models.

Another approach to linking models is the Joint Warfighting Center's Data_Bus. In contrast to the other approaches discussed here, Data_Bus seeks to minimize the modifications needed to federate models. It loosely synchronizes model execution and allows the federation to run on a network of similar computers. However, there is no automated interaction between models federated using Data_Bus; for example, there is no automated power projection between federated models.

Like Cronus, ALSP was developed by ARPA. Several ALSP applications exist and additional federations are planned. ALSP tightly synchronizes events in federated models. It also assures full interaction between federated models, allowing a platform in one model to project power in another. ALSP requires substantial modifications to the models being federated. It also needs special software, such a Cronus, to handle communications between models that run on a network of dissimilar computers. Perhaps the most ambitious ALSP application developed to date was a confederation of the Corps Battle Simulation (CBS), the Research, Evaluation, and Systems Analysis (RESA) model, and the Air Warfare Simulation (AWSIM), which was developed for Exercise Ulchi Focus Lens 1993.

Appendix B

STATUS OF MODELING AND SIMULATION

This appendix presents an assessment of modeling and simulation in terms of their ability to support the needs of the U.S. unified commanders in the current world situation. We will look individually at training simulations for Joint readiness, deliberate analysis, real-time analysis, wargaming, and field analysis. In each of these areas, we will examine both the status of and challenges for modeling and simulation. As we proceed, several themes will become apparent.

Training Simulations for Joint Readiness

Status. Our ability to provide training simulations for the non-military aspects of national security is in poor shape - we simply do not have what we need. Training simulations for non-traditional military activities and operations are in somewhat better shape, but can still only be considered fair. In this area, the Joint Task Force Simulation (JTFS) is under development. The Joint Conflict Model (JCM), a Janus variant, is being developed as the primary exercise driver for JTFS. However, JCM is primarily an execution-phase model that needs to be supplemented with expert role-players and other models to assure adequacy of training in the pre-execution phases of crisis action.

Janus is primarily a land warfare model; JCM's naval, air, and intelligence capabilities have been improved to allow its use as a driver for joint exercises. JCM's report generation capabilities and electronic feeds to real-world command and control systems have been upgraded to allow us to train personnel in their own command centers. Other models, including the Enhanced Naval Wargaming System (ENWGS), have been used in conjunction with JCM in JTFS-driven exercises. When mature, JTFS will provide substantial capabilities to train for peacetime activities and operations as well as low- to mid-intensity conflicts. In addition, the Joint Theater Level Simulation (JTLS) is scheduled for use as a simulation driver for Exercises Cobra Gold and Keen Edge. Training simulations for traditional military operations are in reasonably good shape, as witnessed by establishment of battle simulation centers at I Corps in Fort Lewis, Washington and in Korea and development of model suites and federations to support Exercise Ulchi Focus Lens.

Challenges. Our challenges in training simulations for Joint readiness are to: develop training simulations for the non-military aspects of national security; develop simulations that address all six phases of crisis action, not just execution; develop methods for integrating results from distributed models and redistributing them to a geographically dispersed training audience; developing techniques for easing data base preparation; developing interfaces with real-world command, control, communications, computer, and intelligence (C4I) systems; and reducing the size of training support teams.

Deliberate Analysis

Status. As noted above, deliberate analysis is the traditional military operations research that most of us have been doing for the last several decades. For the non-military aspects of national security, we have some tools (not all within DoD) that allow us to provide limited support for political and economic analysis. Our capability there can be characterized as "fair". In contrast, we are in poor shape for supporting analyses of non-traditional military activities and operations, i.e., those at the lower end of the Continuum of Operations (Figure 1). Existing models cover only a few types of peacetime activities and operations and low- to mid-intensity conflicts. In many cases, we need a better understanding of underlying phenomena before we can begin to develop models. For traditional military operations, we are in good shape, with numerous models and data bases available. This reflects the huge investments the U.S. Department of Defense has made over the last several decades and the reduced demand we foresee for models of traditional military operations.

Challenges. Our challenges in deliberate analysis are to: develop understanding of underlying phenomena, especially for non-traditional military activities and operations; develop models for the non-military aspects of national security; federate models to eliminate manpower-intensive and error-generating "air gaps"; integrate our models with master data bases; and develop (or improve), federate, and distribute models for analysis of non-traditional military operations.

Real-Time Analysis

Status. Real-time analysis was one of the first areas of development and application for military operations research, and is once again emerging as a major functional area. Real-time analysis seeks to bring analysis support to operators in near real time, i.e., in time to influence operational decisions. Analysts at the U.S. Central Command performed numerous quick-turnaround analyses during Desert Storm to support operational planning. However, our overall ability to support operations with analysis is not as good as might be hoped. We have nothing to support real-time analysis of the non-military aspects of national security. For non-traditional military activities and operations, our capability is fair. Models are available for only a few activities and operations. These include DART for personnel and materiel movement; the ARPA Planning Initiative, which will provide a capability to support noncombatant evacuation operations; and the Air Courses of Action Assessment Model (ACAAM), which is being developed as a prototype distributed planning aid for contingency Joint air operations. In general, we need planning aids, decision aids, and execution aids to support real-time analysis of non-traditional military activities and operations.

For traditional military operations, we are probably in fair shape, given the existence of models and data bases for these operations and their lower likelihood. However, our ability to support these operations depends critically on the availability of time and access to models, data, and expertise.

Challenges. Our challenges in real-time analysis are to: develop models for the non-military aspects of national security that can support real-time decision-making; develop (or improve), federate, and distribute models for real-time analysis of non-traditional military activities and operations; assure rapid access to models, data, and expertise; and provide planning aids, decision aids, and execution aids to cover all phases of the crisis action process.

Wargaming

Status. Our ability to use models for conducting wargames of the non-military aspects of national security is poor; we tend to rely on role players rather than models. The availability of qualified role players is frequently a major constraint in conducting wargames of this type. For non-traditional military activities and operations, our modeling and simulation capabilities are fair. Models are available for force tracking and combat resolution, and DART is available for personnel and materiel movement. However, most of our models primarily address the execution phase; we need models for the pre-execution phases of crisis action as well. For some types of activities and operations, we need a better understanding of the underlying phenomena, and where the phenomena are understood, we need to have models developed. Our capabilities for wargaming traditional military operations is good, reflecting the numerous models and data bases available and the likelihood of low demand for wargaming these scenarios in the future.

Challenges. Our challenges in modeling and simulation for wargaming are to: develop an understanding of the phenomena underlying many types of activities and operations, where Lanchester's equations do not apply; develop automated techniques for playing the non-military aspects of national security; develop methods for playing the pre-execution phases of crisis action; develop models for many types of activities and operations; improve the flexibility of game formats to provide greater coverage of the continuum of operations; and reduce the size of game support teams.

Field Analysis

Status. Although the Services have done field analysis for many years, our greater reliance on Joint forces and the doctrine of "training as we plan to fight" introduces a new requirement for observation, reconstruction, and analysis of Joint operations and exercises. We have no experience on which to base analysis in the non-military aspects of national security. Similarly, we have virtually no experience in analyzing non-traditional military activities and operations, where we have a need to resolve numerous contingency JTF doctrinal, organizational, command and control, and training issues. We have a fair capability for analyzing traditional military operations because of significant experience in Service-specific field analysis, but have limited experience with analyzing Joint operations.

Challenges. Our challenges for field analysis are to: develop an experience base for reconstruction and analysis of non-military and non-traditional military operations and exercises, and to extend our Service-specific experience in field analysis to Joint operations and exercises.

Model Development and Federation

Status. As a preliminary summary of modeling and simulation capabilities in the five functional areas discussed above, our ability to provide analytical support for the non-military aspects of national security is poor. Existing models in this area are inadequate. Our ability to support non-traditional military activities and operations is also poor. We need a better understanding of the phenomena underlying many types of activities and operations, models need to be developed for the operations where the phenomena are understood, and existing and developmental models need to be integrated into systems of models. For traditional military operations, our analysis support capabilities are good, based on the existence of several federations of large-scale models.

Challenges. Our challenges for model development and federation are to: develop an understanding of the phenomena underlying many types of activities and operations; develop or improve models for the non-military and non-traditional military aspects of national security; and federate models as they are developed or improved. In this last area, our challenges include observing Common Operating Environment (COE) standards to assure openness of our model federations to future enhancements and managing model federation approaches to maximize their utility.

RIST PRIZE CALL FOR PAPERS

MORS offers two prizes for best papers—the *Barchi Prize* and the *Rist Prize*. In the past, the *Barchi Prize* has been awarded to the overall best of those papers presented in the Working Groups, while the *Rist Prize* has been awarded to the best of those papers presented in the General Sessions. Beginning with the 62nd MORSS, the ***Rist Prize*** will be awarded to the best paper in military operations research submitted in response to this **call for papers.** The *Barchi Prize* will be awarded to the best paper from the entire symposium, including Working Groups, Composite Groups, and General Sessions.

David Rist Prize: Papers submitted in response to this call will be eligible for consideration for the *Rist Prize*. The committee will select the prize-winning paper from those submitted and award the prize at the 63rd MORSS. If selected, the author(s) will be invited to present the paper at the 63rd MORSS and to prepare it for publication in the MORS Journal, *Military Operations Research.* The cash prize is $1000. To be considered, the paper must be mailed to the MORS Office and postmarked no later than **September 16, 1994.** Please send the original, three copies, and a disk.

Richard H. Barchi Prize: Author(s) of those papers selected as the best paper from their respective Working Group or Composite Group, and those of the General Sessions at the 62nd MORS will be invited to submit the paper for consideration for the Barchi Prize. The committee will select the prize-winning paper from among those presented and submitted. The prize will be presented at the 63rd MORSS. The cash prize is $1000.

PRIZE CRITERIA

The criteria for selection for both prizes are valuable guidelines for presentation and/or submission of any MORS paper. To be eligible for either award, a paper must, at a minimum:

- Be original and a self-contained contribution to systems analysis or operations research;
- Demonstrate an application of analysis or methodology, either actual or prospective;
- Prove recognizable new insight into the problem or its solution; and
- Not previously been awarded either the *Rist Prize* or the *Barchi Prize* (the same paper may compete for but cannot win both prizes).

Eligible papers are judged according to the following criteria:

Professional Quality

- Problem definition
- Citation of related work
- Description of approach
- Statement of assumptions
- Explanation of methodology
- Analysis of data and sources
- Sensitivity of analyses (where appropriate)
- Logical development of analysis and conclusions
- Summary of presentation and results

Contribution to Military Operations Research

- Importance of problem
- Contribution to insight or solution of the problem
- Power or generality of the result
- Originality and innovation

Topological Network Designs and Analyses for the Defense Information System Network

Martin J. Fischer
Virginia O. Sielen
Gregor W. Swinsky
Sen-Lang Wang

Center for Engineering
10701 Parkridge Blvd.
Reston, VA 22091

ABSTRACT

Defense Management Report Decision (DMRD) 918 established the Defense Information Systems Agency (DISA) as the central manager for the Defense Information Infrastructure (DII). The DII is the worldwide consolidation of all fixed and mobile DoD information systems. The Defense Information System Network (DISN) provides the information transfer network for DII. It is the DoD's primary worldwide telecommunications and information transfer network for supporting the warfighter on a global basis. The goal of DISN is to provide an integrated network supporting voice, data, video and other value added services. The Center for Engineering (CFE) within DISA is responsible for providing engineering support to the DISN Program Manager (DISN PM) to ensure an orderly and cost effective evolution of this network. A significant part of CFE's contribution to date has been in the area of developing and analyzing network designs for the DISN PM. In this paper we present some of the more representative case studies (designs and analyses) that we have conducted, and show how the tools of Operations Research have played a substantial role in the solution to these problems.

INTRODUCTION

Defense Management Report Decision (DMRD) 918, see [1], established the Defense Information Systems Agency (DISA) as the central manager for the Defense Information Infrastructure (DII). The DII is the worldwide consolidation of all fixed and mobile DoD information systems. The Defense Information System Network (DISN) provides the information transfer network for DII. It is the DoD's primary worldwide telecommunications and information transfer network for supporting the warfighter on a global basis.

The goal of DISN is to provide an integrated network supporting voice, data, video and other value added services. It will be composed of military-base level and regional networks interconnected by a global long haul transmission network. It will provide connectivity among many joint military elements and deployable components. The main capabilities and services to be provided by DISN are:

- End-user to end-user information transfer service through a state of the art wide area and base-level information transport infrastructure. This includes new technologies such as distributed modeling and

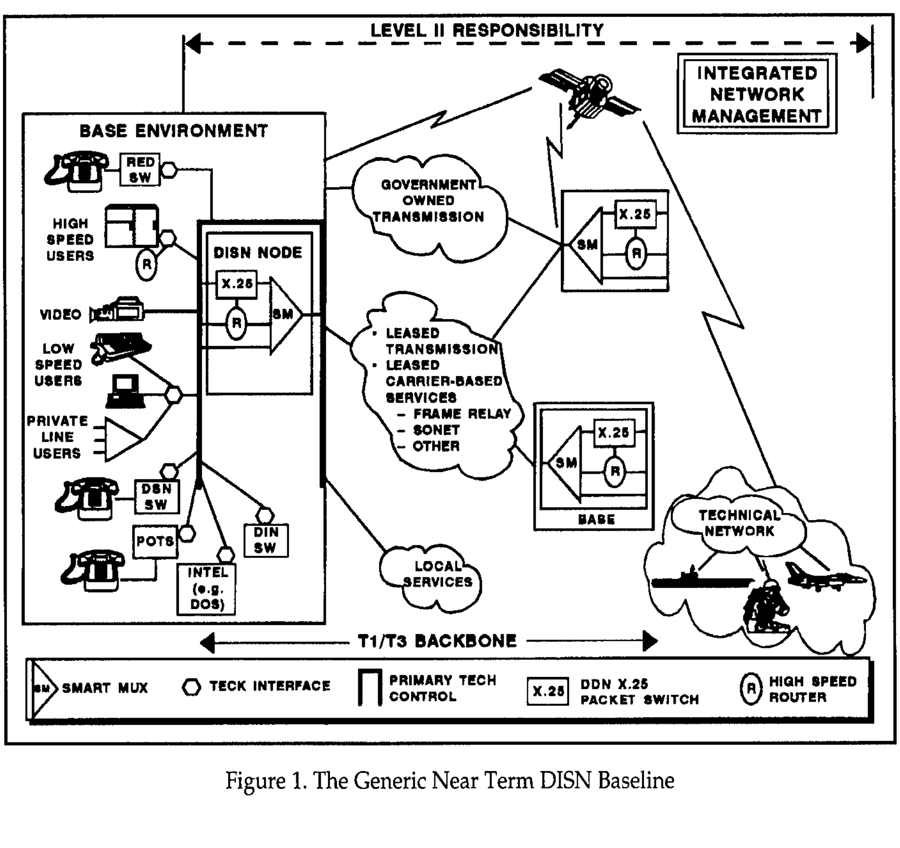

Figure 1. The Generic Near Term DISN Baseline

simulation, distributed computing, and the insertion of ATM and SONET.

- Switched packetized data, imagery (video teleconferencing, audiographics), circuit-switched data, and switched-voice.

- Transmission service facilities (full-period and on-demand bandwidth).

The DISN Near Term (DISN-NT) integrates into a single network many independent Service and Agency smart-multiplexer networks such as the Air Force Network (AFNET), the Navy Network (NAVNET), the Defense Logistics Agency Corporate Net (DCN), several other continental US (CONUS) based smart multiplexer networks, and overseas networks like the Pacific Telecommunications Network (PCTN). A smart multiplexer is a multiplexer that has the ability to automatically manage the transmission network. If new circuit requirements are placed on the network, it will route them over the network's spare bandwidth. In addition, in the event of network failure, the smart mux will re-route circuits around the problem.

The basic DISN-NT architecture is shown in Figure 1. It consists of a transmission backbone composed of smart multiplexers interconnected by government owned and leased T1 and T3 circuits. The DISN-NT node has a DDN X.25 packet switch, an access or hub router and the smart multiplexer that provides access to the transmission backbone. For a more in-depth description of DISN, see [2], [3], and [4].

The Center for Engineering (CFE) within DISA is responsible for providing engineering support to the DISN Program Manager (DISN PM) to ensure an orderly and cost effective evolution of the DISN. A significant part of CFE's contribution to date has been in the area of developing and analyzing network designs for the PM. We have been concentrating our efforts mainly in CONUS, and have developed a goal network design and an optimal near term design, see [5] and [6]. In addition, we have performed numerous other designs and analyses (for example, integration of video teleconferencing into DISN).

We felt that it would be of interest to present some of the more representative case studies (designs and analyses) that we have conducted and show how they have significantly contributed to the orderly evolution of DISN. We propose to show how the tools of Operations Research have played a substantial role in the solution to these problems. In the process we discuss the algorithms we used to solve the problems and relate these applications to actual designs we have conducted for the evolving DISN. In [7] our experiences in conducting these and similar types of designs were presented. Jo (see [8]) has also conducted some analyses for the DII.

In the next section of this paper we discuss the types of network design problems facing the evolving DISN. In the process of conducting these designs many classical Operations Research problems were encountered. The following section discusses these problems, relates them to the DISN network design problems and presents the algorithms we developed to solve the problems. The application of all of this to actual designs is given in the case studies we discuss in the next section. The last section presents the results of our work and conclusions.

TOPOLOGICAL NETWORK DESIGN PROBLEMS FACING THE EVOLVING DISN

The current DISN Near Term is the composite of nine smart-mux networks, seven in CONUS and two in OCONUS. A smart-mux transmission network is composed of links and nodes. At each node there is a multiplexer that muxes low speed circuits on the user side onto the higher speed T1 or T3 lines interconnecting the nodes. A backbone link connects two nodes of the network and may be made up of a combination of T1 and T3 lines. An access area link connects a user to a backbone and may be a T1 line or a lower speed circuit. A smart multiplexer automatically manages the bandwidth in transmission network — that is, if new circuit requirements are placed on the network, it will route them over the network's spare bandwidth. In addition, in the event of network failure, the smart mux will re-route circuits around the problem (also using spare bandwidth). Thus, a smart-mux network is a transmission network that satisfies user requirements in the form of point-to-point circuits and ensures that the circuits will be available to the users at all times. For more details on what smart-mux networks are see [8] or [9].

The basic network design problem for transmission networks, as discussed in [9], is to determine the number and placement of smart multiplexers, the homings of circuits to multiplexers and the development of high speed backbone transmission over which to route these circuits. The backbone links are either T1 or T3 circuits. A T1 circuit is a line that can transmit 1544 kbs; a T3 is composed of 28 T1's. A typical user requirement may be one or more 56 kbs point-to-point circuits. Thus, twenty-four lower speed circuits can be carried on a single T1 line. The tariffs are not linear; five or six 56 kbs circuits between the two endpoints may cost the same as a T1 line. The same non-linearity holds for T1's and T3's, except that the break-even point is higher. The optimal network design is the one that minimizes the total network cost: access, backbone and mux costs.

The Center for Engineering is the lead network designer for the DISN. Most of our work has concentrated on CONUS DISN, which is composed of seven disjoint networks that were independently developed by the Air Force, Navy, and other DoD services and agencies. Currently, the backbone links of these networks are T1 lines. Because of the non-linearity in the tariffs mentioned above, many of these lines are not fully utilized; but since the networks are not connected, one service or agency cannot take advantage of spare capacity on another network. In addition, each network has its own network manager and control facility, which is quite expensive. DISA is the central manager of these networks and has the responsibility to integrate them into a responsive, cost-effective network that will satisfy current and future requirements. The CFE has been developing network designs and conducting analyses in support of this transition.

The topological network design problems facing the evolving DISN fall into two broad categories: defining the goal topology and developing strategies and supporting designs that ensure an orderly evolution to the goal topology. A related issue deals with the insertion of new technologies and services into the evolving DISN.

Obviously, the goal topology has to be defined before any transition strategy can developed. In defining the goal topology we must answer the following questions:

- How should the network be structured? Should there be a hierarchy of backbones (for example, low speed circuits ride a T1 mux backbone, which in turn rides a T3 network), or should the structure be flat (all circuits are homed directly to a T3 backbone)? The hierarchical structure has a wider distribution of hubbing points, bringing the backbone into more areas. The flat structure is more expensive, but is simpler to manage. Which is preferable?
- How many backbone hubs should there be? The more hubs, the lower the access area (user site to backbone node) cost and the higher the backbone and hardware cost. What number of backbone hubs minimizes the total network cost?
- Where should the backbone hubs be located? Should the DISN T3 backbone be hubbed at vendor sites, or is it cost-effective to get T3 service at government locations?
- How should the backbone hubs be interconnected? The issues here are cost, network performance (delays, connectivity, robustness, etc.), survivability, and expandability.

Once the goal topology has been defined, transition plans can be developed. These plans provide road maps to get from the existing networks to the goal DISN. The questions that have to be answered here are:

- How can disparate networks best be integrated? The goals are to minimize disruption, maintain service, and minimize cost.
- If a new network is to be created from scratch, which hubs and links should be installed first?
- In the initial stages of implementation, network capacity may be limited. Which user circuits should be loaded first to yield the biggest savings?

The insertion of new technologies and services into the evolving DISN poses a similar set of questions. Two of these questions are:

- How can routers, voice and video be integrated into DISN? Each of these technologies has its own special type of service need, yet all will eventually ride the DISN transmission backbone.

- To what extent should DISN provide bandwidth on demand? Video service requires a large amount of bandwidth (on the order of a T1) but not all the time. The normal requirements that use this network are full period; that is, available twenty-four hours a day. How does one design DISN to meet non-homogeneous user demands?

These are some of the questions that have to be answered when we develop designs for the evolving DISN. In the next section, we discuss the role played by Operations Research in answering the questions posed above.

ALGORITHMS FOR SOLVING DISN NETWORK DESIGN PROBLEMS

In the previous section, several typical network design problems and questions were presented. We have found four basic types of problems that continually appear in the design of the evolving DISN. They are:

- The concentrator location problem.
- The transmission backbone layout problem.
- The bandwidth packing problem.
- The network performance and reconfiguration problem.

All four of these generic problems either directly or indirectly use the basic tools and methodologies of Operations Research to develop algorithms to solve that class of problem. Once an algorithm has been developed to solve a problem, it can be used either separately or with the other algorithms to answer the types of questions posed in the Topological Network section. The case studies discussed in the next section will elaborate on this in greater detail.

In the concentrator location problem, we are given a set of candidate locations at which to place multiplexers. The problem is to pick the best subset of these locations, to minimize both the cost of homing the users to the multiplexers and the cost of the multiplexers themselves. We have formulated this as an Integer Programming problem and solve it using Lagrangean Relaxation.

The transmission backbone layout problem is considerably more difficult; we have formulated it as a Nonlinear Programming problem. Here one must determine where to place links in the backbone and how to size the links in order to meet certain network performance criteria and to minimize cost. We have developed a drop and add algorithm to design transmission backbones; it generates an initial topology, drops links until it cannot save money, and then goes into an add cycle where links are added that also save money. This process continues until no further drops or adds are possible.

These two algorithms can be combined to solve the overall generic network design problem. That is, given a set of user point-to-point circuit requirements, how many and where should muxes be placed, what is the user homing to these muxes, and what is the backbone network that supports these users at minimum cost. The way we use the two algorithms is to tell the concentrator location model to pick the best "k" hubs from a list of potential sites. Once it solves that problem, a backbone traffic matrix is generated from the user homing, and the backbone design algorithm lays out an optimal backbone interconnecting the "k" hubs. The "k" is then increased and the process is repeated: we continue in this fashion until we find the "k" that minimizes the total network cost. For an in-depth discussion of the concentrator location algorithm and the backbone design algorithm, as well as their combined use to solve the overall network design problem, see [9].

The bandwidth packing problem is one in which the network is given and an additional set of circuits is to be added on the spare bandwidth of the network. We want to choose the most profitable set of circuits to add. This problem has been solved by others using a Tabu Search technique, see [10]; we have used Lagrangean Relaxation to solve it. Since our approach has not yet been published in the open literature, we present the formulation and structure here. Additional information is given in [11].

One is given a network whose links have spare bandwidth and a set of circuits that are candidates for placement on the spare bandwidth. The profit associated with the placement of a circuit on the backbone is known. The problem is to determine which set of circuits to place on the backbone to yield the largest profit. A circuit enters the network at one node and leaves at another, thus it needs to be placed on free slots on one or more links of the network. It can have more than one path in the network. We assume the bandwidth required by each circuit and the spare bandwidth are in the same units. For the T3 network the spare bandwidth on the network is the number of available T1's on each link and the circuits being considered for placement on the network are T1 circuits.

Each link of the network has T(j), j=1,2,...,N, free slots (where N is the number of links in the network). A circuit assigned to link j it will occupy one or more of these slots, depending on the circuit's size. Our initial formulation of the problem assumes that a circuit i has one and only one path in the network over the spare bandwidth, traversing K(i) links. For circuit i, i=1,2,...,M, we have a profit P(i,j) that could be achieved if circuit i is assigned to link j. But there are constraints that have to be satisfied; first, circuit i must be assigned to all links in its path or not at all. This is accomplished by setting P(i,j) greater than zero for all links in its path and equal to a large negative number for those links not in its path. Secondly, we cannot assign more circuits to a link than there are slots.

The Integer Programming (IP) formulation of this problem is:

$$\text{BWP-Problem: Max} \sum_{i,j} P(i,j)*X(i,j) \quad (1)$$

$$\text{ST} \quad \sum_i X(i,j) \le T(j) \quad j=1,2,\ldots,N \quad (2)$$

$$\sum_j X(i,j) = Y(i)*K(i) \quad i=1,2,\ldots,M \quad (3)$$

$$0 \le X(i,j) \le Y(i) \le 1 \quad \forall\, i,j \quad (4)$$

$$X(i,j) \in \{0,1\},\ Y(i) \in \{0,1\} \quad \forall\, i,j \quad (5)$$

The 0-1 decision variable, X(i,j), is set to 1 if circuit i is assigned to link j and 0 if it is not. If X(i,j) is greater than zero for some i then Y(i)=1 and that requirement is on the network. Link j has T(j) free slots and circuit i has K(i) links in its path. That is, if circuit i's path consists of links j1, j2 and j3, then P(i,j1), P(i,j2) and P(i,j3) are all greater than zero, and P(i,j) for all other j has a large negative value. In addition, we would have K(i)=3.

One wants to maximize the profit (equation (1)) subject to not assigning too many circuits to the free bandwidth on link j (equation (2)) and ensuring that circuit i is assigned to the correct links in its path. This constraint is taken care of by equation (3) and in the problem setup by allowing the profit for circuit i to be positive for those links in its path.

Our solution is based on a Lagrangean Relaxation to the BWP-Problem. For an overview of Lagrangean Relaxation see Fisher [11]. The Lagrangean Relaxation (LR) approach is to relax one or more of the constraints by bring them into the objective function via a set of multipliers. The idea is to create a new problem that is easy to solve. If equation (3) were dropped from the BWP-Problem, the solution would decompose into finding the T(j) largest P(i,j) for each j, which could be solved by a simple sort routine. Equation (3) couples the links and the circuits and significantly complicates the problem. Because this constraint makes the solution very difficult, we bring it into the objective function via a set of multipliers i, i=1,2,...,M.

The LR problem becomes:

$$\text{BWP-LR: Max } \{\sum_{i,j}[P(i,j)-\lambda_i)*X(i,j) + \sum_i \lambda_i * K(i)]\} \quad (6)$$

$$\text{ST} \quad \sum_i X(i,j) \le T(j) \quad j=1,2,\ldots,N \quad (7)$$

$$X(i,j) \in \{0,1\} \quad \forall\, i,j \quad (8)$$

In this formulation we require $\lambda_i \ge 0$, i=1,2,...,M. Note that we have dropped the Y(i) variable from the problem because constraint (3) has been relaxed. Since $\sum_j X(i,j)$ is less than or equal to K(i) for each i, one sees that for a given set of multipliers if $Z(\lambda)$ is the solution to LR and Z^* the solution to the IP problem then

$$Z(F) \le Z^* \le Z(\lambda) \quad (9)$$

where Z(F) is any feasible solution to IP. The left inequality follows from the definition of Z^* and the right from the discussion presented above. Equation (9) allows us to bound the solution to IP and tell how much of a gap there is between the largest feasible solution and the minimum solution to LR that we have found.

For a given set of multipliers two phases must be accomplished: first, one has to solve the BWP-LR, and then one must derive a feasible solution from that solution. We consider both phases to be one iteration of the algorithm. The solution to BWP-LR is straightforward: for link j we sort (P(i,j) - i) and assign the largest T(j) to link j. Therefore, X(i,j)=1 for those T(j) circuits with the largest (P(i,j) - i) and X(i,j)=0 for the others. The second phase of an iteration transforms the LR solution into a feasible solution to the BWP-Problem.

For each circuit three cases may result from the solution to BWP-LR. In the first case, a circuit is not assigned to the network at all. In the second case, it is assigned to all links in its path; in the third case it is assigned to some but not all links. For the first two cases nothing is done in the make-feasible phase. For the case where a circuit is assigned to a subset of the links in its path, we off-load the circuit from the links that it was assigned to. After all such circuits have been off-loaded, there is spare capacity on the links, and each circuit is either assigned to the network or not. Next, we order the circuits not on the network based on their total profit and fill the spare slots in the links from this ordered list. Obviously, a circuit is not loaded onto the network unless it can be placed on all the links in its path.

The profit for the solution to BWP-LR and the profit for the derived make-feasible solution are computed and we update the smallest solution we have found for all the LR problems and the largest feasible solution we have found. If the gap between these numbers is small enough or if we have reached a predetermined maximum number of iterations we quit. If not, we update the multipliers, see [12], and go to the next iteration.

Once we have stopped the iterations we try to swap those circuits not on the network with those circuits on the network. Again the circuits that are not on the network are ordered based on total profit. The circuit with the largest profit and not on the network becomes a candidate to swap with one or more of the circuits on the network occupying the same links. A swap is accomplished with the circuits that would yield the largest net gain in profit while still remaining feasible. This swapping process is continued until no more swaps can be found. At that time the algorithm stops. For extensions of the bandwidth packing problem to the case of no splitting of the requirements, bandwidth on demand, and the multi-path problem see [11].

The most recent algorithm that we have developed is our network performance and reconfiguration algorithm. The problem addressed here is very similar to the bandwidth packing problem. One is given a network with spare capacity and a set of circuits that are to be added to the network. We want to reconfigure the network (make minimal changes) to accommodate the new traffic at minimum cost. There are two phases of this algorithm.

First, one could run the bandwidth packing problem to determine which circuits can be placed on the network and which cannot. For those circuits that cannot be placed on the network, additional transmission must be added. An "add" approach is interactively used to beef up the transmission until the network can carry the traffic. T1 transmission is added to the network based on the latest group of circuits that have not been placed on the network. The bandwidth packing algorithm is run to see if the network can carry the traffic. This process continues until a network is developed that will carry the traffic.

The second phase is to interactively drop underutilized T1's from the network, each time checking to see that the network can carry the traffic. More specifically, lightly loaded T1's are dropped one at a time from the network. After each drop the network is checked to see if it can carry the traffic. The process continues until no T1 can be found to drop.

In both phases a "greedy" algorithm is used to decide which T1's to add or drop. We felt that the Lagrangean Relaxation solution to the bandwidth packing problem, if used in this mode, would significantly increase the run time of this algorithm. Because we needed an algorithm that would solve the bandwidth packing problem quickly and with good results, we developed another greedy type algorithm for this application. In this algorithm, the circuits are first sorted according to direct cost from high to low. Then one by one the circuits are placed on the network based on shortest path. When a link becomes full or there is not enough bandwidth on a link in the given path of the circuit, a new shortest path for that circuit is computed and tried. The process continues in this manner until all circuits have been tried. Although this greedy type solution to the bandwidth packing problem is not optimal, it gives good results very quickly.

Using these algorithms we have developed the required network designs in support of the evolving DISN. Few of these designs were similar, and each usually involved a novel use of the algorithms described above to solve a given problem. In the next section we present several case studies that demonstrate the use of these algorithms in answering the questions which the Topological Network section addressed.

DISN CASE STUDIES

For the past two years we have conducted numerous analyses for CONUS DISN. In this section we discuss four representative analyses that we have conducted using the tools discussed in the previous sections. The case studies are classified into four generic areas:

- 4.a. Development of a goal DISN topology.
- 4.b. Integration of DISN sub-networks.
- 4.c. Insertion of new technology into DISN.
- 4.d. Development of periodic reconfiguration network designs.

• Development of a goal DISN topology

One of the first case studies we undertook was the development of a goal T1 network design for CONUS DISN, see [13]. As described in the first section, DISN was a collection of separate service and agency T1 smart-mux networks. DISA has the responsibility to combine these networks into an integrated, cost-effective and interoperable common user network. One of the first orders of business was to develop the baseline and order-of-magnitude type of topology for the DISN transmission layer. The goal was to design a topology that begins to define the magnitude and scope of the network being developed. It was not expected that this design would be exact or implementable.

The output of the study would be an idealized design that identifies the quantity, the preferred locations, site mux component and sizes, the quantity of user access points, fixed equipment costs and monthly recurring transmission costs of the access area (subscriber to T1 mux) and backbone (T1 interconnection of smart muxes).

Some of the more significant assumptions that were used in the study were: all backbone nodes were NET IDNX-70 multiplexers, whereas at an access node a selection between an ADNX-48, IDNX-20 or IDNX-70 was made. We used the Defense Commercial Telecommunication Network (DCTN) tariff. The base requirement was a set of 9214 point to point circuits, and there were over 250 candidate locations for backbone smart-mux T1 hubs.

The concentrator location algorithm and the backbone transmission layout algorithm were used in sequence to generate a total network cost as a function of the number of hubs in the goal network. That is, for a given number of hubs (say k) the access area design determined the k candidate locations that yielded the minimum homing cost of each subscriber site to the nearest of these "k" locations. After the best "k" were found, a check was made to determine if it was cost-effective to bundle subscriber circuits into T1's from the subscriber site to the T1 hub. Once the access area design was completed, the required input files for the backbone algorithm were generated and a backbone network to support the requirement was developed. Finally, the multiplexer (IDNX) costs were determined for the "k" hub design. The "k" was then increased and the process repeated.

The monthly recurring cost of carrying the 9214 circuits on a direct (non-networked) basis was $14.7M; this cost was the baseline number for our design to beat. Figure 2. shows the results of our design runs.

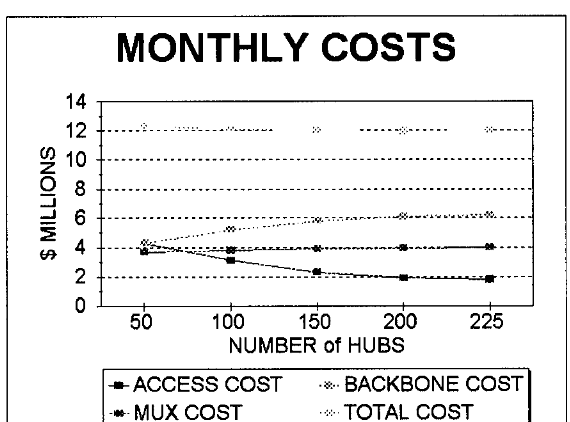

Figure 2. Goal DISN T1 Network Design and Analysis

In Figure 2, four curves were developed as a function of the number of backbone hubs. One sees that as the number of hubs increases, the access area transmission cost decreases, and the backbone transmission and mux costs increase, with the total monthly recurring cost decreasing for hub numbers up to 150 and remaining relatively flat between 150 and 225 hubs. Network management costs are a function of the number of hubs, and so a goal design with 175 hubs and a monthly recurring cost of $11.951M was selected. This design represented a 19% saving over the $14.7M cost of satisfying the requirement directly.

Our work on this case study established two very important points:

- Substantial savings could be achieved if the separate networks were integrated at the transmission level.
- The algorithms we had developed were integral to the orderly evolution of DISN.

The first point became a very strong selling point to the services and agencies who were developing these separate networks and the second point focused all network design work within the Center for Engineering and allowed for scientific analyses to play a pivotal role in DISN.

• Integration of DISN sub-networks

Once the goal topology had been developed, it became important to start to address integration issues and answer "how to" questions dealing with the consolidation of these separate networks into a cost-effective common-user DISN. The first analysis we conducted of this nature was the integration of the Defense Logistics Agency corporate network (DCN) and the Air Force network (AFNET). These networks were the two largest subnetworks to be integrated, and were based on different multiplexer technologies.

The AFNET multiplexer was the IDNX family of multiplexers, developed and marketed by NET; the DCN multiplexer was the ACCULINK family of AT&T multiplexers. These multiplexers were not completely interoperable; each had network management capabilities that required all the multiplexers in the managed network to be of the same type. Thus a complete or seamless network integration was impossible without replacing a significant number of one type of multiplexer.

In 1991 the CFE functional multiplexer analysis, see [14], concluded that the IDNX family of multiplexers best met DISN's functional requirements when compared to the other multiplexers on the market. So in October 1991 the Defense Information Systems Agency announced that the IDNX family of multiplexers would be the DISN multiplexer, see [15].

At this point, two alternatives were considered:

- leave DCN as is, put all new requirements on AFNET, and install bridges between the networks.
- let DCN users become subscribers to AFNET and use their ACCULINK muxes at the user sites and not as tandem multiplexers in the backbone.

The first alternative was rejected because it would require separate (and costly) network managers for both DCN and AFNET, and because it would not fully utilize DCN transmission. Therefore we conducted a study to determine the cost savings of homing DCN users into AFNET (i.e., the second alternative).

We conducted this study in the fall of 1992. At that time the DCN had 63 nodes, of which 30 were collocated with AFNET nodes. The study involved placing an IDNX-20 (low end of the family of IDNX muxes) at the 33 sites that were not collocated with AFNET, and then homing those sites to the nearest AFNET multiplexer. The DCN users at AFNET-collocated sites were homed directly into the AFNET muxes. Next we designed a new AFNET backbone to carry the additional DCN circuits. We compared the cost of integrating DCN into AFNET as just described with the monthly recurring cost of doing nothing. The monthly cost of DCN was $378K for transmission and $381K for the muxes, yielding a total of $759K.

The monthly cost of the IDNX-20's at the 33 non-collocated DCN nodes was $94K, the transmission homing cost $155K, and the additional transmission that had to be added to AFNET to carry the DCN traffic was $157K, for a total cost of $406K to integrate DCN into AFNET. Therefore there was a potential savings of $353K per month from integrating DCN into AFNET.

We used the concentrator location algorithm described above to home the non-collocated DCN users to their nearest AFNET node. The number of concentrator sites to be opened ("k" in the discussion) was set equal to the number of AFNET nodes. The cost delta of adding the DCN traffic to the AFNET backbone was determined by two runs of the transmission layout algorithm: one with the AFNET traffic only and the other with AFNET plus DCN traffic.

• Insertion of New Technology into DISN

The advances in technology within the telecommunications industry have been remarkable. With the advent of fiber the bandwidth available for multiple and diverse types of applications to be sent over the same transmission lines is increasing rapidly. Up to 1993 the basic DISN transmission line has been T1 (1544 kbs). Since the DISN is an integrated common-user network for multiple services, DISA decided to develop a T3 network in CONUS. A T3 line has the same bandwidth as 28 T1's but costs only as much as 12 to 16 T1's. Two problems with T3 service are that it is not available throughout CONUS, and that there are significant access charges from the user locations to the T3 Points of Presence (POP). The upgrade to T3 service is only an interim step toward higher-speed (commonly called OC) rates.

We conducted two analyses, both of which were aimed at determining the potential cost savings of going from a T1-based network to a T3-based one. T3 POP locations played a pivotal role in both studies: the first study assumed AT&T T3 POPs, while the second assumed T3 POPs at government locations. The second study was aimed at examining the impact of local T3 access charges. Before implementing the second study, negotiation with T3 vendors would have to take place.

The two designs were structurally quite similar, with a few minor exceptions. For each design, we had a data base of 1303 T1 circuit requirements and a list of candidate T3 hubbing points. The problem was the same as the one discussed above — that is, determine which and how many nodes are to be T3 hubs, the access area homing cost to the hubs and the minimum cost of T3 backbone transmission between the selected hubs. One difference between these studies and development of a goal DISN topology was that not all the requirements were placed on the backbone. If a T1 requirement's direct cost was less than the cost of homing it to the T3 hubs, then that T1 was not placed on the backbone; instead, it was routed directly.

Another difference was that we had to modify the backbone transmission layout algorithm for this study. The initial algorithm assumed that T1's were being leased on the backbone, but here the base unit is a T3. In addition, there could be situations where a link (connection between two backbone nodes) did not carry enough T1's to cost-justify a full T3, and so any link could be composed of T1's, T3's, or a combination of the two. These modifications to the algorithm were straightforward. The structure of the algorithm when designing a T1 backbone network was to pack the requirements (which were lower speed circuits than T1) into an equivalent number of DS0's (one DS0 = 64 kbs and there are 24 DS0's in a T1), and drop and add links, each time determining how many DS0's are using the link. Each link is then sized based on the DS0's using it. The link add and drop process continues until no more savings can be achieved.

For the T3 design, the requirements are in terms of T1's (one T3 has 28 T1's). The only required algorithmic change was the replacement of the DS0-to-T1 logic with a T1-to-T3 module. As mentioned above, there is a distinct but simple difference between the two design applications: In the DS0 to T1 case the backbone links are always T1's. In the T1 to T3 case the backbone links may be T1's and/or T3's, depending on whatever is most cost effective. Consequently, the module that converts the carried T1's on a link to T3's was modified to determine the optimal combination of T1's and T3's to satisfy the requirements riding the links.

The 1303 T1's came from 352 user sites and could be satisfied at a direct (non-networked) cost of $4.69M per month. In the study that placed T3 hubs only at AT&T T3 POPs, the optimal design had 32 T3 hubs and a monthly cost of $4.29M, for a savings of 8.5%. Figure 3. shows a map of this design.

Based on these results, DISA initiated the implementation of a six-hub, six-link T3 network from the East to West coast. That network is shown by the larger circles and thicker links. Each of the links in this initial network had only one T3, whereas in our full 32-hub design, some of them had more than one T3. We were asked to determine the most cost-effective subset of T1 circuits to ride this initial sub-network. For this study, we did not have all the tools we needed. In particular, we did not have a tool to solve the bandwidth packing problem discussed in [10]. Using Unix utilities, we manually tried different combinations of T1's to be loaded onto the network until we arrived at a set of 90 T1's that would save around $124K a month. After we finished the study and had more time, we developed the bandwidth packing algorithm using Lagrangean Relaxation as discussed in section 3 and tested it on the six-node, six-T3 problem. We found 89 T1's that when placed on the network would save several hundred dollars more per month more than the 90 T1's we originally found. DISA is in the process of implementing this network; the first T3 between Arlington, VA and St. Louis, MO is already in place. The original goal was to have the other five in by the end of 1993, see [16], but negotiations with the vendors and the local customers have slowed the migration process.

One disadvantage of hubbing the T3 network at vendor POPs is the leg costs to get from the user locations to the POPs. This motivated us to look into what savings would be achieved if T3 service were available at government locations. We used the same design approach as in the AT&T-POP T3 hub design, except that our candidate T3 hubbing sites were now a set of government locations, plus the six AT&T T3 hubs in the initial network. (Our algorithm lets a user bolt in a specified set of hubs that will always be selected regardless of cost.)

The resulting design is shown in Figure 4. It has 38 T3 hubs, 32 at government locations and 6 at AT&T T3 POPs. The monthly recurring cost of this network was $4.00M, which is a savings of 14.7% over the direct cost of the T1's. It is almost

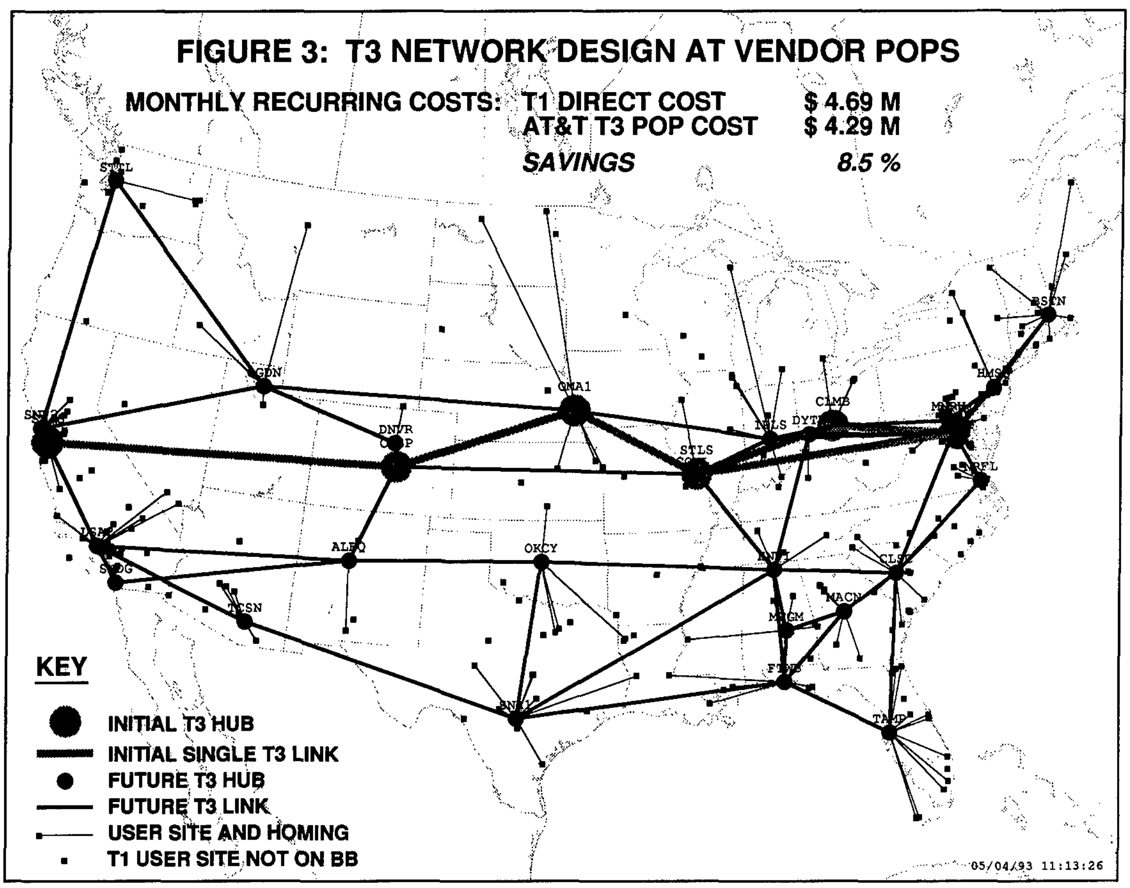

Figure 3. T3 Network Design at Vendor POPs

twice the savings of the all-AT&T-hub alternative, and has inspired DISA to investigate vendor interest in extending their T3 service and tariff to government locations, see [16].

• Development of Periodic Reconfiguration Network Designs

No network design is perfect, and periodically any network needs to be reconfigured based on additional traffic or a change in existing traffic patterns. The same is true for a new network like DISN; perhaps even more so. We have just conducted one such study for the AFNET.

The Air Force did an outstanding job in fielding a network with advanced technology to meet projected requirements. They realized that the combination of smart multiplexers and inexpensive T1 transmission could be used to significantly reduce their telecommunications budget while allowing them to integrate many services, such as bandwidth on demand, over the same network. Using appropriated funds they developed a network based on communities of interest and their best projection of potential users. They did not have the initial user community to make the network cost effective, but instead used a philosophy of "build the network and the users will come" to develop and implement a smart multiplexer network known as AFNET.

AFNET is at the stage where an analysis is required and a reconfiguration needs to be undertaken to optimally align the network with the user community. As it has evolved, one needs to know how far from optimal the current network is, whether it can be reconfigured to place it on a path towards a near-optimal topology, and how should this transition take place. We have conducted an analysis, see [17], aimed at answering some of these questions.

The Air Force gave us data with the operational

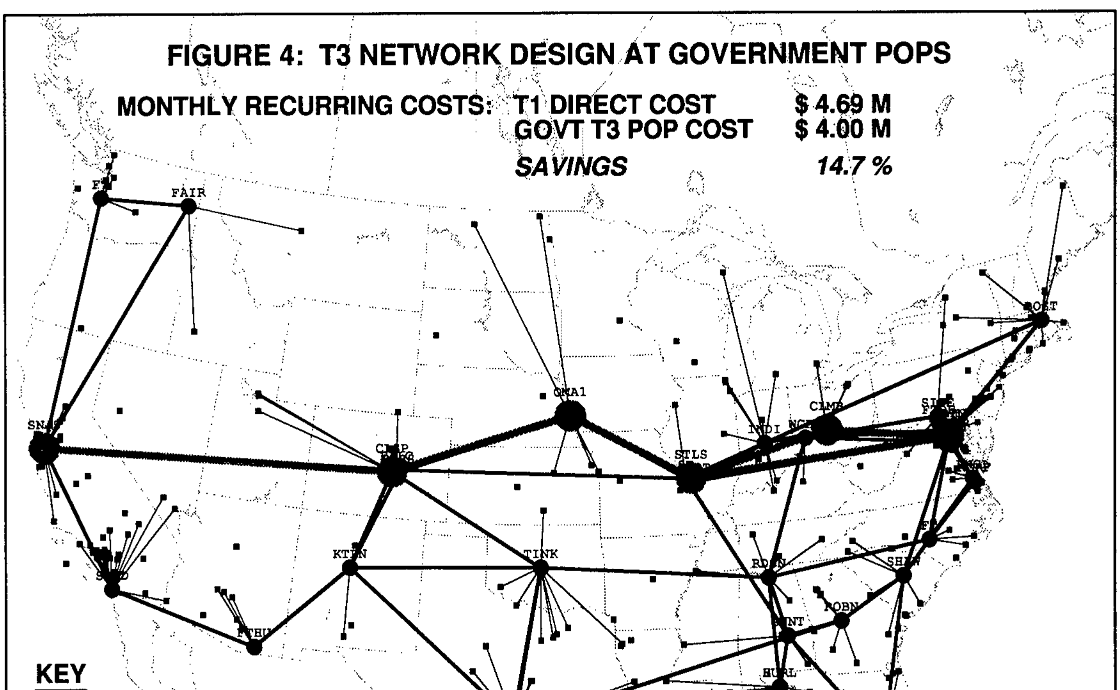

Figure 4. T3 Network Design at Government POPs

AFNET topology, and the circuits riding it. An additional list of 442 circuits (Project 5000) was developed by the DISN program management office (DISN-PM); these circuits were to be loaded onto AFNET. The DISN-PM asked if we could suggest implementable changes to AFNET that would carry the additional traffic.

In this problem we had an existing network with spare capacity; we were interested in determining if the additional traffic could be accommodated using the spare bandwidth. If not, then how should the network be reconfigured to accommodate the additional traffic? The first part of the problem is the bandwidth packing problem discussed above; the second part is a design problem. We used the network performance and reconfiguration algorithm discussed in section 3 to conduct this analysis.

According to the data we received from the Air Force, the operational AFNET backbone had 315 T1's costing \$1.108M per month, with approximately 1800 circuits riding it. The backbone T1's were approximately 70% utilized on average. Our design loaded the 442 Project 5000 circuits onto this network and reconfigured the backbone as necessary. The resulting topology had 317 T1's and cost \$1.085M per month, see Figure 5. The savings of \$23K resulted from the deletion of 15 T1's from the original network, and the addition of 17 T1's in other places in the network. Our design carried the additional 442 circuits and at the same time reduced the network's cost. As a partial validation of our recommendations, we looked at the measured utilizations of the 15 T1's that we suggested deleting and found them to be underutilized.

Our analysis showed that the operational AFNET was not optimal with respect to the traffic that was riding it and the proposed traffic that was being added to it. To determine how far from

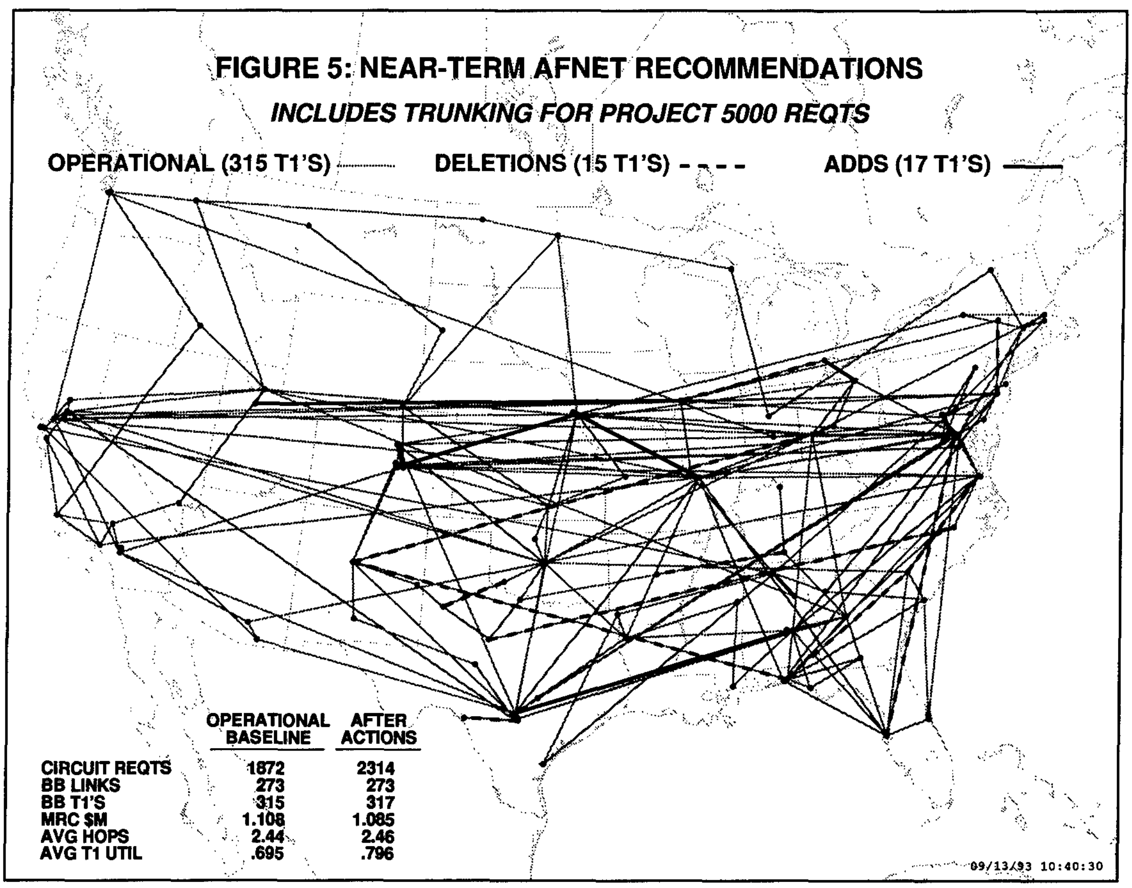

Figure 5. Near-Term AFNET Recommendations

optimal it was, we used our mux network design algorithm to develop an optimal topology. The optimal network had 301 T1's and cost $983K per month. So the operational AFNET was $125K per month more expensive than the optimal network yet could not carry the additional Project 5000 circuits. As might be expected, the two networks were significantly different (see figure 6) — only 118 of the T1's in the operational network appeared in the optimal design. The problem of aligning the operational network more closely to the optimal is an interesting one all by itself. The DISN-PM is in the process of implementing the results of our analysis.

SUMMARY

We have discussed the set of computer algorithms that we have developed to design and analyze the evolving DISN. We demonstrated the use of these algorithms on four representative studies that we have conducted. It has been our experience that each study we do is unique and presents its own set of challenges.

We are continuing to find new applications of the tools of Operations research that allow us to meet these challenges successfully.

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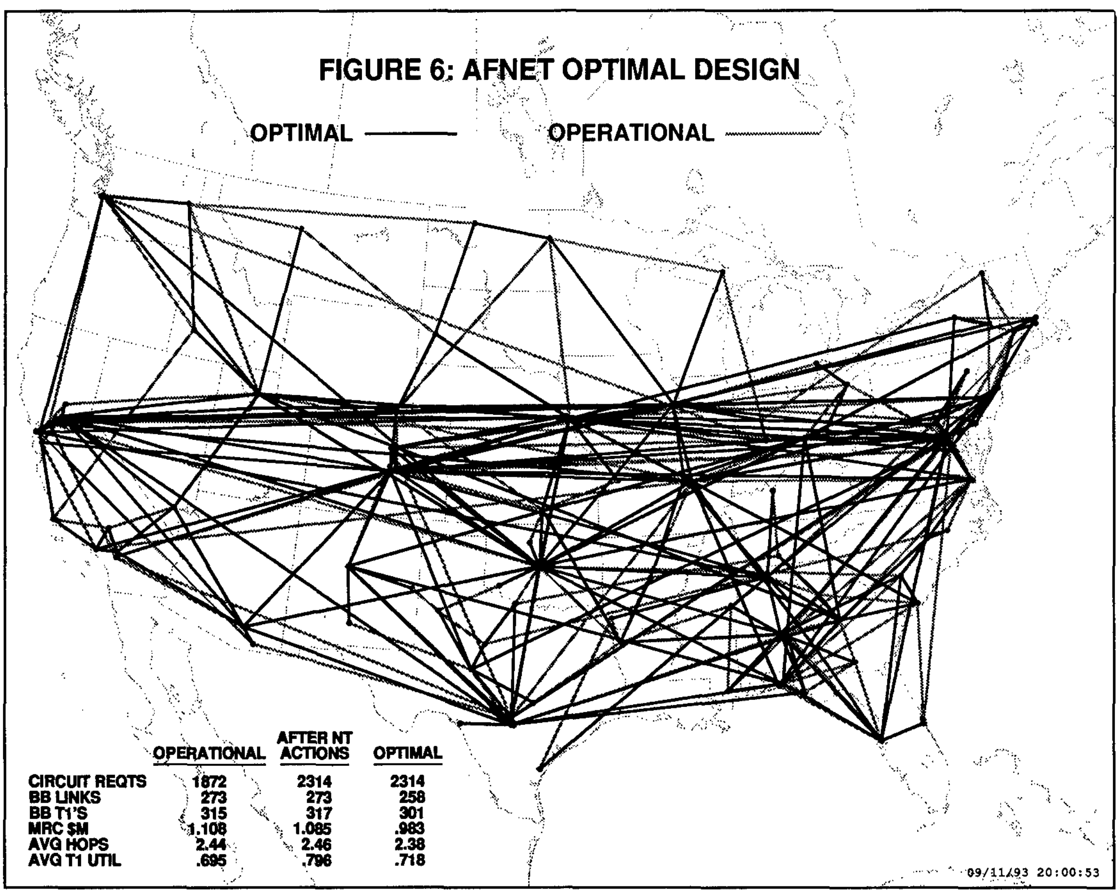

	OPERATIONAL	AFTER NT ACTIONS	OPTIMAL
CIRCUIT REQTS	1872	2314	2314
BB LINKS	273	273	258
BB T1'S	315	317	301
MRC $M	1.108	1.085	.983
AVG HOPS	2.44	2.46	2.38
AVG T1 UTIL	.695	.796	.718

Figure 6. AFNET Optimal Design

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From this uncertainty of all intelligence and suppositions, this continual interposition of chance, the actor in War constantly finds things different from his expectation: and this cannot fail to have an influence on his plans, or at least on the presumptions connected with these plans. If the influence is so great as to render the predetermined plan completely null, then, as a rule, a new one must be substituted in its place; but at the moment the necessary data are often wanting for this, because in the course of action circumstances press for immediate decision, and allow no time to look about for fresh data, often not enough for mature consideration.

- K. von Clausewitz
On War

Chance favors the prepared mind.

- Louis Pasteur

INTRODUCTION

Uncertainty in combat is a very big subject, pervading nearly every aspect of combat theory, including

- the setting in which command decisions are made
- the effectiveness of decision implementation
- the dependability of plans and expectations
- the purpose and value of combat analysis

We will examine the relationships between chance, probability, risk, surprise, and security as factors in combat. The axiomatic umbrella term is uncertainty.

Uncertainty is a subject that pervades the science, art, and poetry [1] of combat in equal measure, and plagues the discussions of scientists, military leaders, and philosophers. I wish to emphasize that it is partly a matter of perspective whether one views combat as highly random and stochastic or highly determined by participants' choices, both deliberate and inadvertent. To show this I introduce some insight, taken from OEG Report 69 by B. O. Koopman [1953]. Koopman dealt with the operational value of a physical phenomenon: sonar detection. He wished to know whether when all the variables were taken into account, a specific sonar would detect at a fixed, certain range, a phenomenon called a "definite range law." In the 1950s, a surface ship sonar detected at short ranges of about 1500 yards, so it was feasible to conduct a closely controlled test. Destroyer sonars were run past a target submarine at known ranges. After isolating as many influences as possible, it was apparent that initial detection ranges were still variable, and sonar detections on submarines remain so to this day. After the test Koopman concluded that sonar detection ranges were more than likely deterministic, but there were other important variables not accounted for in the test. He went on to say that even if sonar detection range was deterministic, in actual operations many of the influences known to have major effects on detection range and fixed in the test would be highly variable during screening operations, so that for all practical purposes sonar detection range would have to be treated as if it was a stochastic process.

Now this must be added: very often the stochastic representation of sonar detection performance (a "lateral range curve") can be set aside and without any loss of predictive accuracy. A simple definite range law (a half "sweep width") can be substituted for computational purposes. In many circumstances, a stark, determin-istic sweep width will yield predictions that are precisely as accurate as if the complex lateral range curve had been used.

It is small wonder that discussions of uncertainty and chance become muddled. For one isolated hardware component of naval combat effectiveness, a QHB sonar (later improved and redesignated the AN/SQR-4 and AN/SQS-4), we have seen that (1) it is possible to believe determinism in principle, (2) determinism must be rejected in operational practice, but (3) determinism as a *model* of a probabilistic phenomenon can be assumed in many circumstances and used without any loss of predictive power whatsoever. Perspective or context is often the key to understanding—or misunderstanding. When people disagree, it is about the extent and pertinence of uncertainty and determinism in combat.

Perspective is the nub of the issue. Command is interested in victory, that is, mission success with acceptable loss of combat potential relative to the enemy's

Commentary

Uncertainty in Combat

Wayne P. Hughes, Jr.
Senior Lecturer
Department of Operations Research
Naval Postgraduate School
Monterey, California 93943

The following commentary is taken verbatim from a forthcoming monograph entitled "Combat Science: An Organizing Study." The whole monograph follows and elucidates a theory of combat developed by The Military Conflict Institute. TMCI's theory is constructed upon core definitions and six axioms. Axiom 6 is "Uncertainty is inherent in combat."

Some important terms that appear below are defined elsewhere in the monograph, among them, combat potential, combat power, and the attributes and states of elements. Their meaning will be clear enough, I believe. Terms related to uncertainty will be defined herein.

loss. Command accepts that it will not know before, during, or even after a battle all the stochastics of it. Given an advantage in combat power that is large enough, command can predict one outcome, a victory, "for all practical purposes". Much of combat analysis is concerned with achieving an advantage that will be determinative. Nevertheless, from the perspective of a man in a tank in the first wave of an overwhelming armored force, many personal outcomes are possible, and his part of the battle is full of uncertainty and risk.

Determinism is not synonymous with complete knowledge or absolute truth. "Determined" expresses the condition in which the record of past events or a prediction of future events is so accurate that any deviation from absolute truth—the actual states of elements— is inconsequential relative to the practical application of the knowledge.

DEFINITIONS AND RELATED ISSUES

Uncertainty is a state of doubt about the past, present or future combat situation, including the outcome.

Chance is an unexpected and unexplained cause of an event that happens without discernible human intention or observable cause. Accident is a synonym [2].

Risk is the possibility of loss or harm. In combat it is some compound of the natural odds (probabilities), the degree of uncertainty (incomplete knowledge resulting in doubt), and the adverse consequences of an unfavorable outcome (the cost of error). Hazard is similar but not a synonym.

Deterministic means that a predicted or observed result is so accurate that any deviation from prediction or observation is inconsequential relative to practical application. Deterministic is not synonymous with "completely known."

Before proceeding, the reader is encouraged to read the discussion *Determinism in Combat* in the Addendum, written by Paul Moose of the Naval Postgraduate School. This will clarify what is meant by random (stochastic), deterministic, risk, chance and probability.

DISCUSSION OF COMPONENTS

Figure 6-1 shows the major components of uncertainty. Postulate for the moment that perfect information is at hand regarding the attributes, location and motion (the state) of all physical elements, and further that all these objects' behaviors are entirely deterministic. This knowledge would be gained from (1) perfect data of the weapons, modes of movement, existing terrain and weather, and by perfect discipline among troops; and (2) perfect and instantaneous knowledge of all positions and movements at the time of observation, so that we have a complete picture of the present. This is depicted as Situation 1 in Figure 6-1.

Even in a deterministic environment there remain uncertainties about the future. We do not know what the enemy will do. Chess illustrates a contest with complete knowledge of present (and past) conditions in which the outcome is nevertheless uncertain. Nor can we foresee future events in nature: chaos theory is the study of the limits of prediction about processes that are deterministically described, operating on objects whose initial states are fastidiously specified! Nor can we be sure that orders will be acted on as intended even when troops execute with the best of motives what they believe are their orders.

Consequently a combat outcome on a deterministic battlefield would still be uncertain, its future course would appropriately be described stochastically, and it would be seen by the commander to involve risk, sometimes even chance.

When we relax the artificial postulation that physical objects behave deterministically (Situation 2 in Figure 6-1) we have at best a probability distribution on their performance, and in addition, will have to contend with events whose pattern we do not know: "accidents" governed, we would have to say, by chance.

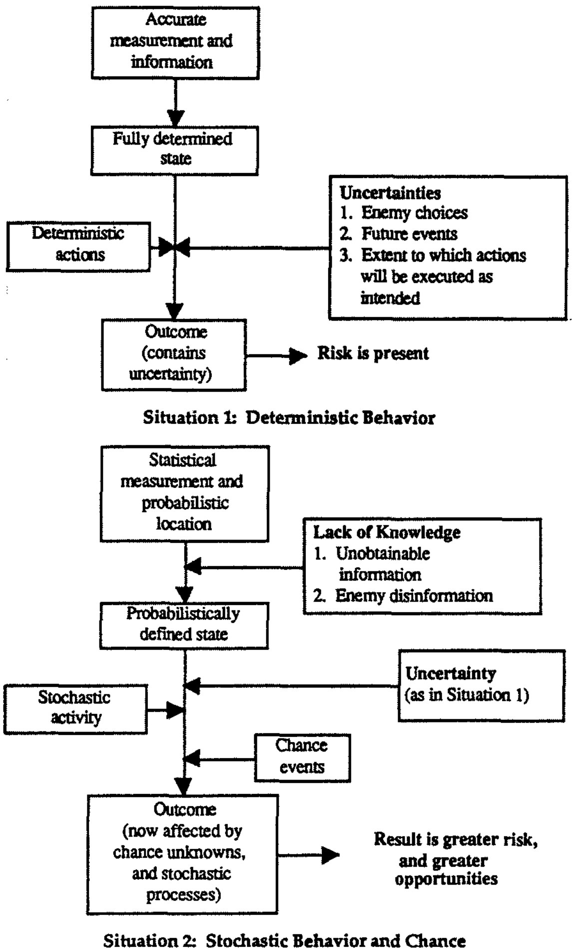

Figure 6-1: Elements of Uncertainty

When we relax the additional postulation that the state of all objects is known we introduce uncertainty that comes from lack of knowledge, including inadequate intelligence about the enemy, data about own forces, disinformation from the enemy, and disinformation (usually inadvertent) about own forces. As we have said, even if all information could be had after enough time, timeliness of decision is a taskmaster that will always proscribe a complete picture. The lack of knowledge regards present states. The same severe shortage of information compounds regarding future activities.

The consequence is not only a priori uncertainty, but certainty that chance will enter into the outcome. Naturally the effect is greater risk.

One technicality must be dealt with. Uncertainty is defined as a state of doubt about the combat situation. Occasionally a combatant will have no doubt but will nevertheless not know the situation. Simple ignorance arises when he does not know what he does not know. More complex ignorance arises when he is deceived: perfect deception would be the result when the enemy misleads a combatant to be absolutely certain but totally wrong about the combat situation. The possibility of negative information is a plague on any mathematical construct describing a state of knowledge. It would be convenient if the state of knowledge could be bounded by, say, zero representing no knowledge and one representing complete knowledge of locations and movements. But if one admits either disinformation, and in all conflict one must, or predisposition, and in all human endeavor one must, then the range of knowledge states must take negative values, in which the combatant is better off knowing nothing than being deceived by the enemy or by his own prejudice. We finesse this problem and subscribe to the usual definition of uncertainty as a cognitive state of a combatant in which when knowledge is received uncertainty diminishes. Misapprehension about the situation, that is, certainty that is unjustified, is a special circumstance which represents a cognitive state worthy of special, advanced study.

Another source of legitimate confusion about uncertainty is simply how one goes about deciding cause and effect. It has been called the "teleological problem" [Thomas, 1989, pp. 263-265]. In the Introduction to the complete monograph it was observed that to verify the predictions of their mathematical models physicists have to specify initial conditions and measure the results with great care. The whole of predictive science is centered on this capability. With either combat or combat models boundary conditions are a perplexing challenge. We face the question of where to cut off accounting for the causes of results, and on the outcome side, where to stop counting the downstream effects of a battle. In social science, understanding is clouded and uncertainty grows to the extent that one insists on admitting remote causes of the course of a battle. Here is Thomas quoting me:

Teleology is the study of final causes. A model always asserts a certain cause and effect, even when it has sophisticated feedback loops . . . We assume a cause when we write inputs . . . The model not merely asserts presumed first cause, but circumscribes for its user the world of admissible cause.

Consider a warfare example: Why did Lee lose at Gettysburg? Historians may take as the proximate cause the ill-considered charge of Pickett on the third day. Or possibly Meade's artillery, massed in the center.

As causes "once removed," there was Meade's astute tactical leadership and Lee's uncharacteristic error. But few historians stop there. The cause was "really" Jeb Stuart's absence, so that Lee fought blind. Or the earlier death of his stalwart Stonewall Jackson.

Deeper still, it was simply the inevitability that sooner or later the odds would catch up with Lee, and his daring battlefield tactics would overextend him. The fundamental cause, therefore, was the Union's greater mobilization base. Lee was impelled by a sense of urgency, knowing that time was against him. Thus, what historians may call a tactical blunder was Lee's last-gasp gamble, a gamble made with a thoroughgoing appreciation of the true odds against breaking through the center.

None of the "causes" above is unimportant, and the list is by no means exhaustive. One could add the Union quartermasters' efficiency ("logistics dominate war"), the motivating reasons why the soldiers fought tenaciously, etc., etc.

All the causes contributed to the effect: the Confederates lost the battle. Any model of it will emphasize some things and deemphasize others, even to the point of exclusion. Whether the model is the analyst's simulation or the historian's description, it circumscribes the event with some set of cause and effect relationships. Any model, even the most ambitious, is vulnerable on ground of sufficiency—its omission of the n-th order "cause-of-a-cause-of-a-cause. . ."

Thomas is as incisive as can be on this subject. Here he is referring specifically to model validation, but what he has to say is equally apt for historiography, operational planning or strategic interpretation of battles.

UNCERTAINTY IN THE CONTEXT OF THE THEORY

During a campaign (or in peacetime) a commander must compare strengths and make forecasts using combat potential and a vision of how forces will be employed. His aim is favorable results when battles ensue. A higher commander assigns forces to the battle commander based on relative combat potential and other factors, but the generation of combat power is not within his control. The battle commander activates potential to create combat power. He controls the modes of his forces, but he is limited by their designed attributes. An AEGIS naval cruiser is formidable against air-to-surface missiles, but has nothing special to offer against submarines. An armored battalion is superior to light infantry on its own turf but will be victimized in mountainous terrain.

While a commander makes his deployments so does the enemy. Combat effectiveness, or force, is determined by decisions on both sides and the resulting interactions. It is the collision of two forces that determines the outcome of a battle. Only the results are observable. Any attempt to trace the effect of new and better combat potential, as represented by a new sensor, weapon, commander, fighting doctrine or force mix, from cause (combat potential) through combat power, two sided combat effectiveness, and a two-sided outcome leaves a wide gulf of uncertainty. It takes extraordinary insight or unabashed hubris to draw conclusions without examining the intervening gap between combat potential and result, and in peacetime all such examinations are speculative.

I once was charged with corroborating a model and undertook the task by refighting the Falklands War of 1982 on a computer, using the strategies and tactics of the Argentines and British [Hughes; 1986]. The results did not compare well because combat effectiveness in the model was based on armored and mechanized warfare in Europe and the war was fought by infantry. When this obvious defect was repaired, there were still sometimes wide differences. The model said there would be serious casualties to the U. K. transports from air attacks on the day of the landing when there were in fact none. When a model predicts reasonably and history is outlandish, one does not alter the model; one continues to expect troopship losses when a landing is opposed by a massive air attack. There is no gainsaying poor tactics, but one does not often want a model that employs them. [3]

It has been argued that uncertainty plays a bigger part in single events because the central tendency of large numbers cannot play its role. This is disputable on theoretical grounds: only the mean value is better determined or more predictable; the standard deviation of n different variables does increase as $\sqrt{n}$. It is also disputable by the evidence: top warriors achieve remarkable strings of victories. Why this is so, and why the best still may fall, are too large a matter to take up, but it is better to study the determinable factors that build up the strings of victories than to play up the role of chance or luck. Champions retain a sense of the whole contest. They lose some points but they win the tournament.

THE LIMITS OF UNCERTAINTY

A remarkable property of military uncertainty is that after it has been turned over in the hand until all facets are seen, a great deal of combat remains deterministic against our standard of consequentiality. Great leaders themselves tend to discount uncertainty. Nelson's most famous fighting instructions said, "Something must be left to chance," but the same instructions were crafted to eliminate it. Such leaders had battle plans, formally and otherwise, which they expected to be bent and distorted by chance and the actions of the enemy, but not broken. Analysts must be less sure, and lean more heavily on the methods of probability theory. For one thing, the problems *analysts* study are the ones without easy answers: what purpose is served to study the obvious? By contrast a *combat leader* moves heaven and earth to fight only battles with obvious, good outcomes. The rule of war is never to pick on someone your own size. For another, the analyst (except when he is in close proximity to the battle as in the air Battle of Britain) must handle too many variables. He is the man described above who must speculate (an appropriate word) about results when he has at best combat potential to work with, and even that may be potential that exists only on a drawing board.

What we have said argues neither that chance dominates war, nor that uncertainty is unimportant. It argues neither that outcomes can never be forecast, nor that good analysis always makes good forecasts. It would be a narrow interpretation of Clausewitz indeed to conclude that he believed that war was *governed* by uncertainty, or that outcomes were a roll of the dice.

INTERPRETATION

The power of prediction depends, first, on what is demanded of it. A win or lose outcome may be essentially certain when the details are not. That "no plan survives contact with the enemy" is not the same as saying no plan is executed in its important features. The author of the saying, the elder von Moltke, was one of military history's most successful evaders of any evil consequences of uncertainty.

If an advantage in combat power (observe the shift from potential to power) is sufficient and sensibly employed, chance cannot alter the outcome in its significant aspects. If the advantage in raw power is great enough, brute strength will even overcome both poor employment and a more skillful opponent.

Amidst uncertainty, knowledge is still power. The commander and forces with the most information, both technical and operational, have a great advantage. Experienced soldiers believe knowing what *can* be known overwhelms in its importance what cannot, i.e., chance, insofar as aggregate results are concerned. If skill is regarded as a special form of knowledge, many will insist that the advantage in both knowledge and skill will determine outcomes in their major form. This includes skillful defeats, as with Robert E. Lee and Leonidas, as well as victories. "What is called 'foreknowledge'" wrote Sun Tzu, "cannot be elicited from spirits, nor from gods, nor by analogy with past events, nor from calculations. It must be obtained from men who know the enemy situation [1963; p. 145]."

A major part of skill and expertise is recognizing and avoiding situations dominated by uncertainty or chance when superior, and creating opportunities for uncertainty for the enemy when inferior.

The relative value of opposing forces can and should be estimated, as can comparisons between different tactical employments in various combinations. Except when chance intervenes inordinately (the crazy, absurd loss of the nail in the shoe of the horse of the messenger carrying the vital order) the evaluations have predictive power far beyond simple win-lose estimates. We are dealing with the distinction, which is always present, between the realistic "You may expect victory" and the Delphic "You shall have victory." Historians must not take unequivocal predictions by successful leaders literally. These are part of the poetry of commanders.

Once again, perspective is important. The allocation of combat potential by a CINC to his subordinates amidst scarcity can never be greater than approximately right, but it is sufficient for his purpose if he does so with perspicacity. Corbett takes four pages in *The Campaign of Trafalgar* [1910, 43-46] to show that for planning purposes the Admiralty counted a three-decker ship of the line as worth two two-deckers. Mahan says "in current naval opinion one three-decker was better than two seventy-fours [the basic two-decker]" and C. S. Forester expresses the same view. These attitudes (not the historians' but the naval officers') were empirical. The same result can be computed analytically by applying the Lanchester square law to ships' guns instead of numbers of ships [Hughes, 1984, p. 43]. The British admiralty always tried to match an equal number of units, counting a three-decker as two units, not one and one-half, when distributing its combat potential against the French (and sometimes the Dutch, Danish, and Spanish). Equality was deemed sufficient doubtless because the Royal Navy's superior seamanship was an unspoken tie-breaker in battle. But this method of counting was a CINC's device; it was left to the tactical commander to transform his combat potential into combat power effectively.

Let us inquire into the value of *modeling* human performance. All analysis can ever do is create IF-THEN statements. Every model-data pair is an IF that produces a result which is a THEN. When the human factor is stripped out of analysis so that combat is done fearlessly and efficiently, the uncertainty about the data and model is less. Therefore the results appear to be less uncertain. We have artificially created a relatively tight IF-THEN statement because we have entertained fewer variables. In many cases a customer should prefer it that way: he will be happy to have the additional clarity and precision and be content to use his own judgment regarding the effects of human factors. There are other times when ducking the issue of human performance is an evasion of responsibility. Either way, when we add human elements on the IF side we are going to increase, not decrease, the spread of possible outcomes on the THEN side. By including uncertainty about the human element we hope to achieve the positive result of moving the center of gravity of results toward "truth", but we cannot hope to improve the predictive power of the analysis. At best we will have a more accurate mean but a wider variance.

Professional knowledge and discipline contribute in the direction of determinism. The course of a battle was more predictable when Grant fought Lee than when the green Union army met the newly formed Confederate army at First Bull Run. A more subtle manifestation: "deterministic" conditions are often the insight of the informed mind that is able to recognize patterns when the uninformed sees chaos. This is, in classical terms, the *coup d'oeil*, and in modern science, the hoped-for fruits of Chaos Theory itself: macro patterns seen amidst micro unpredictability.

The man who expects to fight without fear of failure is in the wrong profession and should turn to civil engineering where he can apply his knowledge of statics, make his computations of structural strength required, and then triple his estimates to be safe. Still, the soldier makes his estimates, too, in order to to go with the odds.

As for predictive power, only a small fraction of historical, sociological, or other study and analysis of warfare is for the purpose of prediction. The greatest effort and the greatest value is for description. When the description is rigorous we gain understanding. When it is poetic we gain insight. Something similar can be said of quantitative methods: they are used first to test what is thought to be true or good; then we apply them in the hope of learning what might be better. Good description leads first to understanding and insight, next to the power of better decision, and only after that to the desired end: greater combat power on the battlefield. Thus, to ask science how much uncertainty in a battle will affect predictions about its outcome is to ask the wrong question. The question science can answer is how much do chance and uncertainty affect our understanding of the combat phenomenon? The answer is extensively; enough so as to make scientific study of the phenomenon a worthy endeavor, and enough to make it axiomatic in a theory.

STOCHASTIC MODELING

Now I come to a personal interpretation with which some analysts, a minority I believe, and many military leaders, probably a majority, will disagree. It is that the multifaceted nature of uncertainty argues for model simplicity, not complexity. There is a longrunning attempt, especially in the U. S. Army, to learn more and better lessons by building more and more complicated simulations. Elsewhere, including the U. S. Navy and the Joint Staff in the Pentagon, a similar mindset has led to development of very complicated war gaming systems with much stochasticity built in. The argument is that because battles are complicated, the tools of analysis should be, too. Also present is an undercurrent of dissatisfaction with model results, and so more detail is sponsored as the correction. How to make a better model is much of the motivation of this study, but in these discussions the point to be made is that more detail is not the answer, nor in most instances is more stochasticity, that is, Monte Carlo simulation.

I do not believe one disregards uncertainty, I simply do not believe a representation of the true uncertainty can even be approached, much less emulated, in a combat model. In the light of what has gone before, perhaps one clean example will suffice. The Lanchester equations and their many offspring— simple models of force against force— are all deterministic. It is argued that a stochastic version, which is now easily accomplished with computers, is preferable on grounds that combat is made up of stochastic duels. Indeed, Ancker and Gafarian [1988] have shown that the trajectory of the stochastic version leads to a different outcome in a duel to the death, than the deterministic version. What they say is true but irrelevant. The stochastic version describes who kills whom and when, but nothing more. If the stochastic version is more realistic, it is infinitesimally so. One moves a great distance toward understanding combat in its many modes by examining a variety of deterministic force-on-force equations side-by-side with examining battle data for similar situations. He moves about one millimeter further in understanding (or predicting) by tracing through the probability distribution of the two sides' casualties. To believe the use of stochastic Lanchester makes him much wiser, he must believe that only firepower determines results, firing range and movement are inconsequential, mission is irrelevant, territory is immaterial, firepower effectiveness can be determined within a few percentage points, and on and on. In fact for the difference between deterministic results and mean values of the stochastic results to show up, the battle must go on until most of one side are casualties. Such battles are so rare as to be anomalies.

How should one deal with uncertainty? The answer always depends upon the aim, but here are some old truths. One should never believe he has eliminated uncertainty. He cannot. He should never believe he has represented it stochastically in more than one or two aspects. He cannot, so stochasticity should be incorporated at particular times for special purposes. A model should only be as complicated as the considerations that go into the operational plan it supports, which means that it will look a couple of echelons down, should look at as many variations as possible, and should allow for surprises. This is a recipe for breadth, not depth, of analysis. The analysis that went into the design of the Maginot Line was flawless: the line was never breached. The analysis of the defense of France failed because it wasn't expanded out of the context of the Maginot Line.

CONCLUSION

The essential and axiomatic property of combat is not that it is stochastic but that it is suffused with uncertainty. Following immediately is a truism of the most fundamental significance: combat involves *risk* of personal and institutional harm.

Because combat comprises both random and deterministic phenomena, perspective determines how much weight to place on each. For a commander at any level, perspective is top down: the grasp of all things in general and some essential details in particular, toward mission accomplishment. For the analyst it is often bottom up: all influences are possible, so he must choose among them to build up a picture of the battle dynamic sufficient, but just sufficient, to solve a problem.

A good description and understanding come before prediction. If predictive power is the aim, the reduction of risk is a reasonable goal, not the elimination of uncertainty. Neither tactician nor analyst should expect much detail from his prediction *a priori.* Neither should expect much accuracy regarding cause and effect even *a posteriori.* When one visits the Delphic oracle to see the future, he should ask modest questions. His measure of effectiveness had better be coarse grained, like mission accomplishment, not fine tuned, like the movement of things during the battle, the quality of each man's decision, and the state of morale when the fighting is over. These latter measures will always be for understanding, not for prediction.

When a debate occurs over the degree of uncertainty, chance and risk, it is well to define the context carefully. Context is the cause of more dispute than real differences of opinion, at least among authorities.

ENDNOTES

1. The poetry of warfare is an essential concept of the monograph, "Combat Science." To be concise, poetry is the stimulater of the emotions of warriors. It manifests itself as morale, willpower, staunchness, fighting spirit and other human qualities that lead to acts of valor. [page 2]

2. In this study chance will not be used to mean the likelihood or probability of an event occurring. [page 3]

3. I had occasion to talk to an Argentine aviator, Commander A. D. Dabini, who flew scouting missions with S-2Fs. He said, of course his side should have hit the troops ashore and afloat. For an intense, detailed and factual account see Woodward [1992; pp. 222-289]. Admiral Woodward is quite blunt about the aviators' error and its costliness to the Argentine side. [page 7]

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ADDENDUM: DETERMINISM IN COMBAT [1]

Essential Concepts

A priori determinism is the ability to predict events (results or outcomes) in advance. Examples:

- Tidal motion. Chemical reactions. The return of Halley's comet. Everyone will die. In a tennis match, Martina Navratilova will defeat Paul Moose. An aircraft carrier will defeat a gunboat.

Although the prediction may not be exact in every detail and every situation, it is close enough to truth to be considered an accurate prediction.

A posteriori determinism is the accurate reporting "after the fact" of an event or sequence of events. It is a statement of historical fact. Examples:

- Gambling last night, I threw four "seven's" in a row. The Germans lost World War II. Four Japanese carriers were sunk at the Battle of Midway. The USSR had 20 million mortalities in World War II.

Even after the event, there is room for observational error, or incomplete information. Physics' Uncertainty Principle tells us that complete information about subatomic particles cannot be determined even from the most carefully done experiments. But for many practical purposes the position/motion of the particle will be determined well enough to use.

Conclusion: Determinism is not synonymous with complete knowledge and absolute truth. "Determined" expresses the condition in which the record of past events and prediction of future events is so accurate ("full of truth") that any deviation from the absolute truth is inconsequential relative to the practical applications of the knowledge [2]. Also note that absolute truth about known events is itself a construct, which may not be observable, for example from uncertainty principle arguments.

Stochasticity is usually taken as synonymous with "random," and we do so, too. The idea of stochasticity is that we cannot predict a priori which of a set of possible events or sequence of events will occur. However, the event or sequence in question becomes deterministic a posteriori, after it has occurred, and so it is no long unknowable. If, a priori, several events or sequences of events are possible, then we may say we are "uncertain" about which of these will occur; we may ask with what likelihood we think a particular one will occur. Thus we see the intellectual connection between stochasticity, uncertainty, and likelihood. We have established clear distinctions for "uncertainty" and "predictability," but we did so in a way that does not violate usage or their traditional relationship with stochasticity.

Frequently the term *chance* is used synonymously with likelihood, e. g., "all sequences have equal chance" to mean the same thing as "all sequences are equally likely." We will not. We need to reserve a word for the unexplainable occurrence, and we have chosen the word "chance." Which sequence occurs is in our context governed by likelihood or probability.

Illustrations of Concepts

A. **Rolling a "seven" four times in a row with dice.** There are 16 possible sequences of events in the course of rolling two dice 4 times. [S = seven, A = anything else]:

1) S S S S
2) S S S A
3) S S A S
...
...
16) A A A A

A priori I am "uncertain" about which sequence you will roll, but I may compute the probability, or likelihood, that you will roll sequence #1). A posteriori, as reported in the illustration above, I know, if you are truthful, that you rolled sequence #1). There is no more uncertainty about what happened.

B. **A tank battle.** Red and Blue, each with three tanks, fight until one side is reduced to one tank. The possible sequence of events (results) lead to six outcomes:

1) 3,3 2,3 1,3
2) 3,3 2,3 2,2 1,2
3) 3,3 2,3 2,2 2,1
4) 3,3 3,2 2,2 1,2
5) 3,3 3,2 2,2 2,1
6) 3,3 3,2 3,1

Before the battle, the commanders are uncertain about which sequence will occur. They may be interested in their likelihood of "victory," defining a blue victory to be more blue than red tanks left, and vice versa. A priori determinism would guarantee a particular sequence. From a particular tank crew's perspective, determinism would even require knowledge of whether their tank would be a survivor, something that cannot be deduced from the above sequence of events. When the battle is over, the outcome is "determined" a posteriori as 3,1; 2,1; 1,2; or 1;3, as well as the sequence of events (path 1, 2, 3, 4, 5, or 6), and even which tanks survive. But we may not know what has been determined, tank by tank, because we may not have all the data.

C. **Naval Battle Group Air Defense.** This combat situation is so intricate that it can only be described as a coarse-grained series of events:

(1) Long Range Strike Aircraft (LRA) are sent to attack a Naval Battle Group (BG).
(2) The BG has surveillance aircraft (SA) which may or may not detect the incoming LRA.
(3) The BG also has fighter aircraft (FA) which may or may not intercept the LRA, given an SA report of detection.
(4) If the fighters intercept, they may shoot down from zero to all of the LRA.
(5) The surviving LRA (from zero to all) may or may not find and attack the BG and sink or disable from zero to all of its ships.
(6) Surviving LRA rearm and reattack. The battle ends when all LRA are shot down, or run out of missiles, or all ships are sunk or disabled, or the LRA commander stops attacking.

Though this is not a very complicated battle, no one would claim that its progression above is *"a priori determined."* Much uncertainty, even chance, are at work in the detail, for example exactly when and which SA detect which LRA, which FA engages which LRA, how much damage a particular missile will do to a particular ship when it hits, and so forth. Even to enumerate all the event sequences in this problem is complicated: "SA #2 detects LRA #5 at 1506. It vectors FA #6 at 1507. FA #6 fails to intercept at 1512. LRA #5 closes the BG and launches two ASM's at 1521. One missile misses; one hits and severely damages an escort cruiser at 1525" and so forth.

This describes one portion of one event sequence. There are a very large number of possible sequences of events. Which sequence will transpire is very uncertain. However, at some overall level of battle outcome it is still possible to say that because of the numbers and attributes of the aircraft, their sensors, their communications, and their weapons, the winner of this battle "for all practical purposes" is determined. Sometimes we may confidently make this prediction, even though the exact progression of events is undetermined *a priori,* and is unknowable in complete detail *a posteriori.*

Conclusion. Even though all combat at a sufficiently detailed level of description will be uncertain in evolution, some combat processes and outcomes are deterministic *a priori* at a sufficient level of aggregation. Recall that determinism in scientific experiments means results that are predictable to a degree of accuracy such that any deviation from actual outcome is inconsequential.

Measuring Deterministic Phonomena

Although not as vital as measuring uncertainty and stochasticity, even physical science is challenged to decide that phenomena are deterministic. The collection of data and manipulation of it to arrive at conclusions about deterministic cause and effect relationships, models and measurements of them, is of itself an involved task.

MEASURING UNCERTAINTY AND LIKELIHOOD

Probability theory provides a *measure* of the likelihood that a particular event or sequence will occur. Consider two versions of probability theory: "classical probability," and "fuzzy probability." Both are axiomatic, logically consistent theories, but the importance of each and differences between them is in how we interpret the mathematics in practical application. Here are the essential features. In classical probability theory, outcomes are distinct; for example, I either roll a seven or I don't; I either win or lose the tank battle; if one of the six sequences of the tank battle occur, the other 5 do not; and so on. We assign numbers between 0 and 1 to these distinct outcomes which order their likelihood of occurrence and which, classical theory asserts, will be very nearly the ratio of the number of times a particular event occurs to the total number of times we do the whole process over again.

Thus arises the relative frequency interpretation of probability given repeated trials of an experiment or a battle; and what is called the "expected value" of many trials. What is called The Law of Large Numbers is simply a mathematical statement of how close the actual number of occurrences will be to the expected number. As the number of times a controlled experiment (or *identical* battles!) is repeated again and again, the ratio of the average value of the results to the expected value tends toward one. The Law of Large Numbers quantifies, or measures, this central tendency. The traditional interpretation of probability as relative frequency in repeated trials, and the demands for many trials imposed by the Law of Large Numbers, cause concern in the application to combat of probability theory, and its averages, moments, distributions, etc. We shall return to this shortly; first, "fuzzy probability."

Fuzzy probability is based on the notion that many events cannot be stated in black or white, yes or no, terms such as "I won, he lost," or "Blue lost 3 tanks, Red lost one." Many events are "fuzzy," as in "I achieved my objective but suffered more losses than he did," or "Blue had three tanks crippled, while Red had one destroyed." Fuzzy probability provides for results that are characterized by "membership functions," so that a fraction of the result belongs to one event and a fraction to others. A calculus of probability has been developed based on this premise and is in considerable vogue here and in Europe.

Let us return now to the Law of Large numbers and the problem of conducting repeated trials in combat. First of all, probability, as a measure of likelihood, need not be interpreted in terms of relative frequency. For example, a commander may say that based on his experience and estimate of the situation, there are three substantively different outcomes possible in a coming battle, and he "knows," or believes, outcome #1 is three times as likely as either #2 or #3. We therefore assign probability 3/5 to #1, 1/5 to #2 and 1/5 to #3, thus quantifying the relationships he believes in. There is no prohibition of this interpretation of probability theory and its attendant calculus, for example in determining the likelihood of compound events. In this way we avoid the issue of repeated trials, but raise a related issue, namely that of validation.

The second fact is that many random variables (i. e., probability measures) of importance in combat (compound events) do involve large numbers: the number of rounds of ammunition expended per day of combat per infantry battalion, the average miss distance of all bombs dropped by an attack squadron during a raid, the number of messages entering a headquarters each day during an operation, etc. Probabilistic descriptions in terms of means, distribution functions, standard deviation, etc., are often necessary, undoubtedly appropriate, and known to be useful. Expected values (averages) are also useful and sometimes good enough, even when used as though they were deterministic, which of course they are not.

Aggregation is another useful way to deal with a large number of possible results, each with an infinitesimal probability of occurance. This done by defining compound "events": collections of elementary events, so that the probability distribution is less diffuse. Here are two examples:

A. We may define two compound events from the sixteen possible sequences of rolling craps four times. We define events: Z = All sequences with just one A (non-seven), and Y = All other sequences. Compound event Z has four elementary events, while Y has 12.

B. In the tank battle, we may let the compound event W contain all elementary events which have more Blue tanks left than Red, and X be all others. Then W and X each have three elementary sequences in them.

The effect of aggregation is to create compound results (each still technically an "event"). Aggregation has an effect similar to that of repeated trials. In terms of the Law of Large Numbers, the trials required to achieve an "expected value" outcome of the event or sequence is the reciprocal of the probability that the event will occur. Thus, if the probability distribution is very diffuse, that is to say, with many events each with small likelihood, then many trials are required before the average result is likely to occur even once. Aggregating the events aggregates the probabilities. Thus, when the "expected" losses among 1,000 tanks is 500, the probability that exactly 523 will be lost is small compared with the probability that between 400 and 600 will be lost.

CONCLUSION

Any combat can be fractionated practically *ad infinitum* into many, many possible sequences of events by incorporating more and more detail about the men, materials, and processes in the engagement. Clearly such a description is *non-deterministic a priori*, because we do not know which evolution will occur. If one could assign accurate probabilities to all possibilities, then the probability of a particular sequence occurring would be so small as to be valueless in terms of relative frequency. Further, even when we know that a sequence of events in a battle is *determined a posteriori*, usually we will still not know everything about the sequence that occurred. Our knowledge will be limited to what is accurately recorded in the after action reports.

In order to make a useful interpretation of probability and apply the statistics, the battle's components, processes, and events must be aggregated, regardless of the hierarchical level. The coarseness and fineness issue is at the heart of stochastic modeling and its utility for understanding combat. Hence, the issue also determines one's outlook on the predictive power of a combat model, statistics, or historical insights. Predictive power is inescapably intertwined with the granularity issue: how much accuracy in how much detail we require for practical application.

ENDNOTES

1. P. Moose is the author of these observations, in collaboration with W. Hughes. [page 14]

2. Physicists have an even more rigorous, almost pathological, definition of determinism. Strictly deterministic processes, they say, are reversible processes, "those in which there exists a Lagrangian function L[q;q] which is a function only of the generalized coordinates q and generalized velocities q." See R. B. Lindsay, "Physics— to What Extent Is It Deterministic?" *American Scientist*, Summer 1968, pp. 93-111. But observable, reversible physical processes are difficult to find because of friction, and such a standard of

determinism for living systems merely a mathematical construct. What is true of physical systems logically must be true of more complex living systems. We find in R. J. Field "Chemical Organization in Time and Space" *American Scientist*, April-May 1985: "All observed changes that occur in living systems, even the most elemental, that occur due to internal driving forces are irreversible." Therefore, relevant determinism may be taken to be that for which cause and effect relationships can be traced and measured, at least locally. For our purposes the stringency of determinism is relaxed further, and said to be not absolute but relative to the degree to which the causes are specifiable and the results are measurable and consequential. [page 14]

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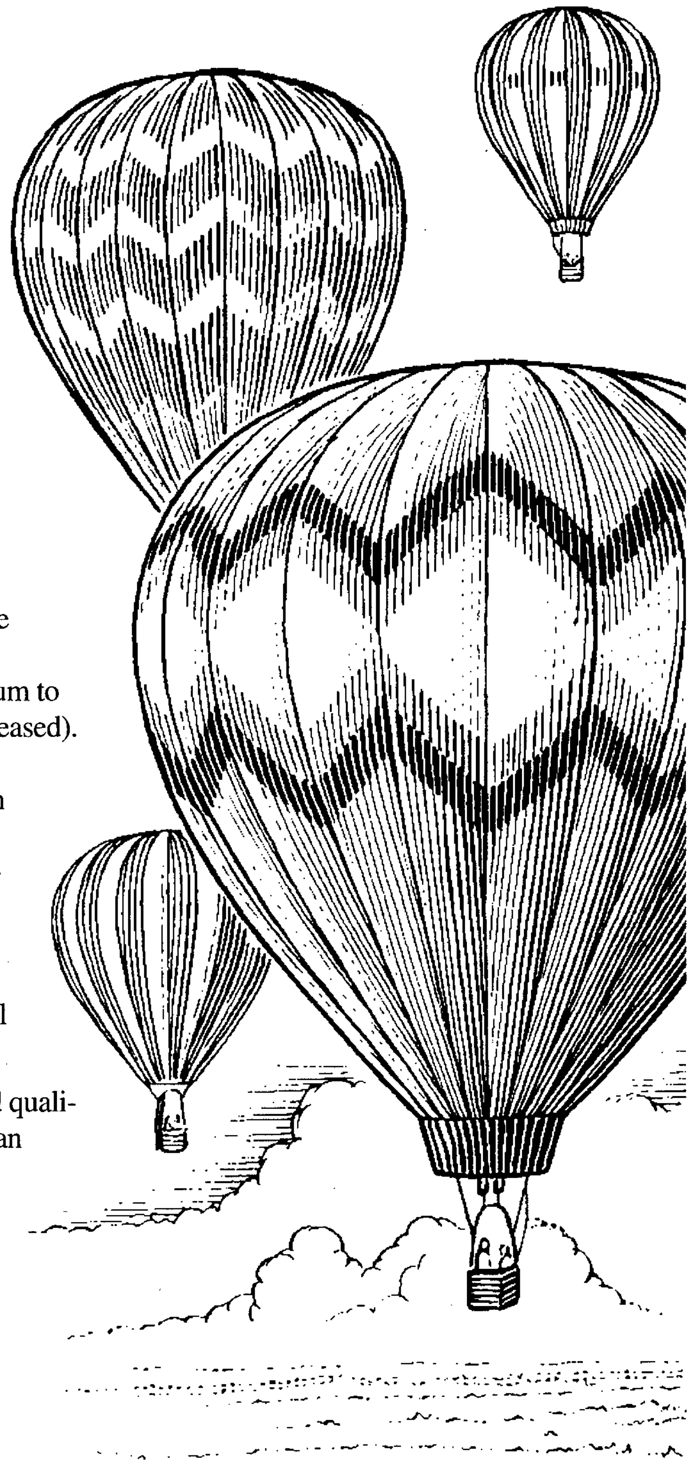

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